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REPORT

Summary

In this report, an evaluation is given of the results of the work that has been performed in Work Packages 1 and 2. This evaluation is done against the following predefined requirements: functional, qualification and data presentation. Furthermore, a benchmarking tool and a decision support tool has been developed and included in the AHMOS II website. Finally, the next steps are identified and suggestions are given for improvements and exploitation.

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Fokker

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EXECUTIVE SUMMARY

To achieve the project goals, the work has been conducted in two Work Packages: WP 1, the technology path and WP2, the flight test path.

In Work Package 1, the technology path, new sensors have been tested and or evaluated for their damage detection capability and some preselected existing sensors have been further developed. In addition, to improve data transfer capacity an ethernet network for AHMOS II has been developed and the microcontroller module has been improved. Data analyses methods have been studied. Data presentation to the maintenance personnel by using a Graphical User Interface via a notebook has been developed. In Work Package 1, to prove the diversity in application of the damage detection systems, several tests have been performed. CASA and ALENIA have performed flight test trials as part of Work Package 1.

In Work Package 2, ground tests and flight tests have been performed to demonstrate the feasibility of operating Structural Health Monitoring Systems (SHMS) in a flight environment utilizing an actual military air vehicle. The focus of the ground tests was on both damage detection (compare system output to actual damage evolution) and system operation using qualified systems.
Flight tests have been done using a Hawk aircraft (BAE Systems) and a F-18 (Patria) aircraft. In the flight tests, the Acoustic Emission, Strain Gauge, Fiber Optic, SWISS and Lamb Wave sensors have been tested together with their complete network. The notebook with the GUI has been used on both the ground as the flight tests.

In order to learn the progress in Technology Level, the Technology Readiness Levels of all used systems have been determined. The highest level achieved is TRL 7 for AE, crack in metal structure, for FBG, strain measurement, for the Graphical User Interface, for Strain Gauge, crack in metal structure (if sensors are correctly positioned), metal stringer disbond (if sensors are correctly positioned), system network and modules and for the Central Computer.

The achievements of AHMOS II and the next steps

Acoustic Emission (AE)
The AE detection technology is real-time. It is designed to operate while the platform is in service undergoing operational loads. Damage detection capability of the AE sensors has again been proven. The capability of damage localization and extent is however not yet proven. Initially, further developments for the in service use of this sensor should focus on “hot spot’ monitoring.

SWISS

SWISS (Smart Wide area Imaging Sensor System) is based on ultrasound. In principle, it has the potential to detect all such damages (e.g. corrosion, cracks, delaminations etc.) that can be detected by ultrasound in conventional inspections. The self-test capability of sensor, sensor-coupling to metallic specimen after instrumentation and under in-service like conditions has been demonstrated. Also, the known-good ultrasound response of known-good (healthy) structure has shown sufficient repeatability to serve as ultimate self-test of the system functioning. Damage has been detected when damage occurred. Localized damage (cracks) in the structure has been detected, localized and quantified. Depending on the specific installation and implementation, SWISS has demonstrated applications specific potential to deal with unexpected (non-lab-like) behavior of hot-spot areas. In summary, SWISS has been used on the ground and the flight tests with application specific success.

Strain Gauges

Strain Gauge technique can be used for damage detection in metallic aircraft structure. Strain Gauge sensors are only suitable for monitoring known 'hot-spots'. The Strain Gauge technique has been used on the ground and the flight tests.

Fibre Optic Bragg Grating (FOBG)

Structural Strain Variation monitoring technique by means of FOBG is real time. It is designed to operate with the platform in operation. FOBG sensors have the potential to detect delamination and debonding in composite material, cracks in metal structure, to do strain measurements and to do fatigue life consumption calculations. FOBG sensors have been tested on the ground tests and flight tests. On ground tests, the damages have been found after post processing of the data.

Lamb Wave

The capabilities of the Ultrasonic Guided Wave (Lamb Wave) system are limited to monitoring of the structural integrity of a region of structure local to the transducer. Therefore, this system is useful only to monitor 'hot-spots' for debonding of joints, cracks and possibly corrosion. Test results show that the system has detected the debond, in real time, during flight-testing, without any false calls.

Eddy current array sensor

The investigation showed that the high-frequency absolute sensor is suited for the detection of surface cracks located just beneath the sensor, and the low-frequency reflection ring is suited for the detection of sub-surface cracks in riveted joint structures. It is recommended to further investigate both sensor types using different and realistic specimen configurations under fatigue testing.

Long period gratings (LPG's)

The investigation concludes that low cost, commercially available equipment based on HRI coated LPG's can provide advanced chemical sensing and liquid monitoring. This basic research has shown the potential of LPG's for SHMS purposes. However, extensive further research and development is needed to prove the usability for SHMS purposes and to become sufficiently mature to be used on aircraft.

Corrosion sensor

This technique is based on the principle that the surrounding structure corrodes at the same rate as the sensor. A corrosion sensor has been used on the Hawk flight test without any result due to not occurring of corrosion damage. Extensive further research and development is needed for this sensor to become sufficiently mature to be used on aircraft. One of the issues to tackle is in-service data validation.

Fiber optic sensor using reflectometric approach.

This work involved testing COTS components and telecommunications as fibres and optical devices to verify the "reflectometer" concept for the detection of the presence of a liquid.

This is a preliminary study based on defining low cost and robust components, and the range of potential measurements likely. The work also includes some practical investigations on the influence of the fibre optic cut quality on the performance of an eventual sensor. This basic research has shown the potential of 'reflectometric approach' for SHMS purposes.

Therefore, extensive further research and development is needed to prove the usability for SHMS purposes and to become sufficiently mature to be used on aircraft.

System network and modules

All parts and modules of the system network that have been used and tested during the AHMOS II are experimental or prototype parts. During the ground and flight-testing it has been proven that they fulfill the functional and performance requirements as needed for the AHMOS II project but that they are not yet fit for definitive in-service installation into aircraft. In order to achieve this, these parts should be further developed (including miniaturization) and further tested on-ground and in-flight for qualification.

Data presentation

In this project, a Graphical User Interface (GUI) by means of a Notebook System has been developed by (NIRAS) DEMEX in order to present damage data and more to the maintenance personnel. The GUI has been used during a ground test and flight tests.

In three levels, information is given about the health status of system and structure to the user. During ground testing and flight testing it has been proven that the level 1 and level 2 functionality of the GUI works as expected. Level 3 information, as far as available, has not completely been used.

Software qualification

In AHMOS II, because the SHM Systems are introduced for testing purposes only and the failure of the system will not influence the operation of the aircraft, Software Criticality Level E (no effect on the system) has been selected. However, at the commercial introduction of a SHMS in (military) aircraft the Software Criticality Level of at least C should be considered.

Hardware qualification

During AHMOS II extensive amount of hardware qualification testing has been performed.
All the system parts that have been installed in the Hawk pod have successfully been tested on the ground and in flight either by suppliers or by BAE Systems. All the system parts that have been installed in the F-18 pod have also been ground and flight-tested. Except for an EMI problem, the system passed all tests.

From the AHMOS II project results the following next steps have been identified:

- Proving 100% reliability of damage detection in the monitored area. This requires extensive testing and validation.
- Further development of damage localization capability.
- Further development of damage extent determination capability.
- Further development of software to provide Level 3 damage presentation data to the Graphical User Interface. In first instance, for one known structural part with damages the 3D presentation should be further developed, tested and validated.
- Hardware and software Qualification of the actual system to be installed.
- Prove 100% reliability of the GUI software.
- Wireless technology.
- Data reduction capability and enhancement of download speed of the Central Computer.
- Standardisation of interfaces (both hardware and software).

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1 INTRODUCTION

The purpose of AHMOS II is:

- To demonstrate the feasibility of an operating Structural Health Monitoring Systems (SHMS) in a flight environment utilizing an actual military air vehicle.
- Further development of:
    - o damage detection capabilities
    - o sensors
    - o systems
    - o presentation of damage data
    - o qualification aspects

To achieve the AHMOS II goals the work is divided in two Work Packages: Work Package 1 “Technology Path” and Work Package 2 “Flight Test Path”. In Work Package 3, the results of these work packages are evaluated and the steps for exploitation and improvements are identified.

Evaluation is performed following the AHMOS II project structure, except the WE activities that were preparational work for either the technology path or the flight test path. Additionally, Technology Readiness Levels have been determined for the systems as developed and tested in this project.

2 TECHNOLOGY PATH (WP1)

2.1 Sensor and Network technologies (WE1.1)

2.1.1 New Sensors (WE1121-2)

The work consists of separate investigations highlighting relevant damage detection approaches not included in the prototype AHMOS SHMS. There were four major activities in this work element (Ref. 3):

- Long period gratings
- Reflectometric approach for chemical sensing
- Develop corrosion sensor
- Develop eddy current array sensor

Long period gratings (LPG's) (WE1121-21, Ref. 4)

This work involved numerical and experimental investigations on the effects of High Refractive Index (HRI) coatings of different thicknesses on LPG devices. The objective was to develop species-specific opto-chemical sensors based on nanoscale HRI polymeric sensitive overlays. The coating material used was thin film syndiotactic polystyrene (sPS) in 150 nm and 300 nm thick layers. This material exhibits a nanoporous structure able to reversibly absorb certain analytes whose size and shape fit nanocavities in the sPS to establish host/guest interactions, the main effect being a strong increase in density and thus refractive index. Theoretical and experimental analysis showed good agreement, and suggested that sensitivity can be correlated with cladding thickness. The investigation concludes that low cost, commercially available equipment (including a spectrometer with a wavelength resolution of 0.1 nm) based on HRI coated LPG's, can provide advanced chemical sensing for VOC's, gases, and liquid monitoring in light of the easy multiplexing capability and lower complexity compared to alternatives such as Plasmon resonance or waveguide sensors.

This basic research has shown the potential of LPG's for SHMS purposes. However, extensive further research and development is needed to become sufficiently mature to be used.

Reflectometric approach (WE1121-21, Ref. 4)

This work involved testing COTS components and telecommunications as fibres and optical devices to verify the "reflectometer" concept for the detection of the presence of a liquid. A "reflectometer" is a fibre optic sensor based on measuring the reflective index difference between a cut glass fibre and the surrounding environment. The reflection coefficient inside the glass dramatically decreases when the open fibre end is contaminated by liquid. This is a preliminary study based on defining cheap and robust components, and the range of potential measurements likely. The work also includes some practical investigations on the influence of the fibre optic cut

quality on the performance of an eventual sensor. Plastic deformation in the core zone may induce case-by-case variability in the reflected light intensity, leading to a lack of absolute measures for the sensor output.

This basic research has shown the potential of the 'reflectometric approach' for SHMS purposes. However, extensive further research and development is needed to become sufficiently mature to be used.

Corrosion sensor (WE1121-22, Ref. 5)

The AHMOS II project includes a corrosion sensor development task as part of the research oriented Work Package 1. BAE Systems was tasked with bringing appropriate technology to the project. Due to parallel developments within BAE Systems, a relatively mature corrosion sensor (or more accurately paint degradation sensor) could be used during this project. The UK programme within AHMOS to flight test a number of structural health monitoring technologies on board a BAE Systems Hawk jet has presented an opportunity to deploy an example of these sensors to raise their Technology Readiness Level to the status of 'demonstrated in a representative environment'.

The corrosion sensor was mounted in the AHMOS flight instrument package (ref. paragraph 3.2 Hawk flight test). It was bonded to the outer surface of the BAE Systems Acoustic Emission instrument box. Leads attached the sensor to a battery powered data logger located inside the instrument box. The data logger is a 'stand alone' unit and completely self-contained. It is not part of the integrated damage detection architecture of the Hawk flight test system.

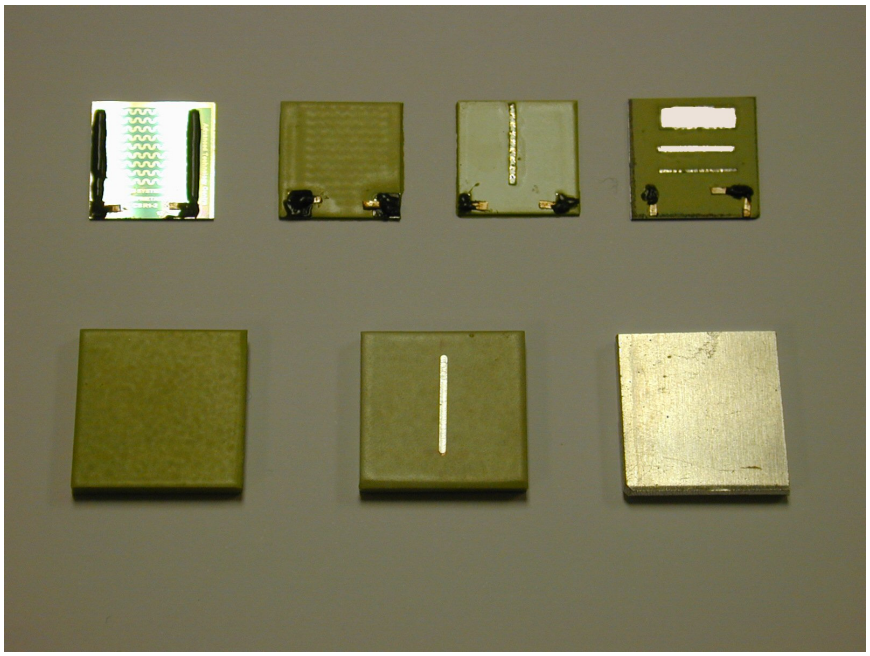


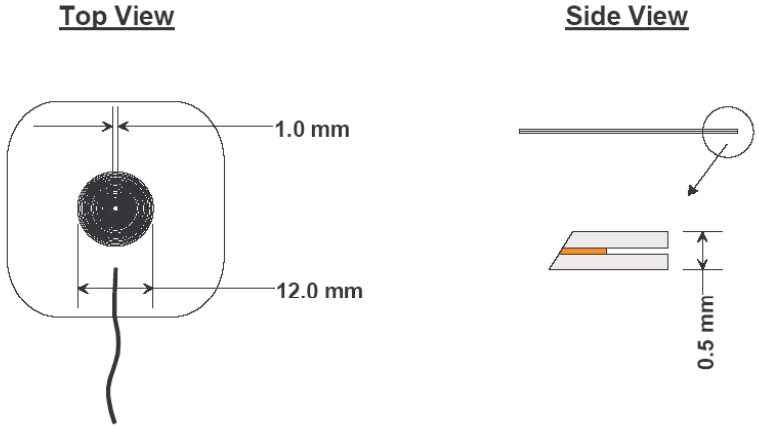
Figure: Family of corrosion and environment sensor designs. The 'Sentinel' corrosion sensor as used in the AHMOS flight test pod is shown top right with windows of varying size in the paint layer. Control samples are also shown in the bottom row

The technique is based on the assumption that the surrounding structure corrodes at the same rate as the sensor.

The corrosion sensor has been used on the Hawk flight test. Because there was no occurrence of corrosion damage, the detection capability could not be verified. Advanced lab trials at BAE Systems, however, showed the corrosion detection capability of this sensor. On other military aircraft outside AHMOS, trials are performed with prototype systems.

Eddy current array sensor (WE1121-23, Ref. 6)

Eddy current array sensors have been investigated by NLR for their potential applicability of local monitoring of hot spots in metal aircraft structures. In reference 6 the detailed results are given.



Flexible sensor for high-frequency surface crack detection

Eddy current inspection (EC) is currently the primary technique for in-service inspection of metallic aircraft components. The technique is based on the response of induced currents that are caused in a conductive material when that material is subjected to an alternating electromagnetic field. Material defects that interrupt the EC flow can be detected by a change in the EC response. An advantage of the technique is that no special coupling medium is required between the inspection probe and test material.

Two prototypes of EC sensors were selected for the present investigation: a thin and flexible high-frequency absolute sensor for the detection of surface cracks, and a low-frequency reflection ring sensor for the detection of sub-surface cracks in fastener holes in multi-layer aluminum structure. Both sensor types work with a MultiScan MS 5800-E™ of Olympus NDT. This is an EC multi-channel acquisition unit with 4 independent probe inputs and up to 64 multiplexed inputs (16 time slots). The sensors were evaluated using a range of test specimens with artificial defects and real fatigue cracks, including specimens under real fatigue loading.

The investigation showed that the high-frequency absolute sensor is suited for the detection of surface cracks located just beneath the sensor. This sensor is flexible and can be bent down to small radii; the sensor produces reliable EC signals for radii down to 7 mm. The low-frequency reflection ring sensor can be used for subsurface crack detection in riveted joint structures. The detectable crack length for this sensor depends on the inspection configuration, the depth of the defects and the test frequency. As a rough indication, defects from about 8 mm at a depth up to 3 mm in lap joints of Glare 4B-0.4 material are detectable. Smaller defects (length < 6 mm) and defects at larger depth (depth > 4 mm) are not detectable anymore.

Both prototype sensors are sensitive to changes in ambient temperature. This should be considered (and compensated for) when performing SHM measurements at different temperature, for example during in-flight and on-ground conditions.

The feasibility and potential applicability of both EC sensor types for the local detection of cracks in metal aircraft structures has been demonstrated. However, much further work is needed. For example, it is recommended to increase the monitoring capabilities of the MultiScan equipment in order to use the system for practical SHM applications. The system should allow continuous operation for periods much longer than one day (main areas of attention are the acquisition rate and the cursor length in the strip chart display of the instrument). It is also recommended to evaluate the multi-sensor capability of the MultiScan equipment using a specified 16-channel switch box (in the present investigation only single sensor measurements were performed).

It is recommended to further investigate both the high-frequency absolute sensor and the low-frequency reflection ring sensor using different and realistic specimen configurations under fatigue testing. The actual limits of flexibility of the high-frequency absolute sensor should be investigated using specimens with smaller radii (< 7 mm). The low-frequency ring sensor should be further investigated for the detection of sub-surface corrosion in aluminum alloy structures.

2.1.2 Existing Sensors (WE1121-3)

This work element consists of separate investigations regarding the capability enhancement of existing sensor systems over the course of the AHMOS project. The report gives an overview of the results of the following two activities:

- Improve functional performance of SGI
- Miniaturize electro-optical interface

Improvement of functional performance of SGI (WE1121-32, Ref. 7)

The strain gauge interface developed in AHMOS I was considered to perform relatively well in structural damage detection (TRL7) and quantification (TRL5) applications. However, the prototype hardware used in the

first AHMOS project was too fragile to be implemented in the harsh (realistic) environment demanded by WP2 ("Flight test path") of the AHMOS II project. For this reason, there were key objectives within WP1 ("Technology path") of AHMOS II for new hardware and software for the Strain Gauge Sensor System (SGSS), using the AHMOS I prototype hardware as the base for this development.

The two major thrusts of development effort were to implement a new communication standard, and to assess and respond to the environmental requirements specified for operation as in-flight equipment. In general, the first of these (i.e. the new communication standard) has been a great success resulting in an increase in communication speed and easier interfacing to other equipment. However, the challenge of addressing the environmental requirements has been less straightforward and has resulted in more substantial design alterations.

The SGSS has now, however, seen the full envelope of F-18 during total of ~11 test-hours and has been operating faultlessly. This means that SGSS is fit for installation in a flight environment.

Miniaturization of electro-optical interface (WE1121-33, Ref. 8)

The space enclosure requirements defined in WP2 ("Flight test path") of the AHMOS II project required a substantial reduction in size of the FBG interrogator used compared to the AHMOS I program. The focus of the WP1 ("Technology path") program in this case is to address the main issues that prevent the technology being commercially applied under operating conditions (size, ruggedisation, operating speed, communications, price), rather than any issues remaining concerning the sensing concept as such.

The key driver in the development was to reduce the volume of the final design by optimizing existing components or by replacing with newly available technology. The miniaturization led to a decrease in volume of the interrogator from 23.2 liters (AHMOS I) to 2.4 liters. This is an acceptable size for use on test aircraft.

2.1.3 System Network and Modules (WE1122)

Two sub-sub-tasks are defined in this work element (Ref. 9):

- Review and improve system network.
- Review and improve system modules.

Review and improve system network (WE1122-1)

In AHMOS I, a CAN-network was used to transfer data between measuring modules and the central laptop. The data transfer capacity of the CAN-network, however, is limited, due to the relatively slow transfer speed and short message size.

A recent trend in data communication is the use of Ethernet-network with Internet related protocols. This technology was also adopted by the AHMOS-group, and new communication technology has been selected to be the backbone of the AHMOS II project. This technology is the Ethernet-network with UDP/IP-protocol on top of it. It has successfully been used in WIWEB and Risø test benches. It has also been tested over the Internet and it has been implemented into the Hawk-pod. No major problems have occurred.

Review and improve system modules (WE1122-2).

In AHMOS I, the microcontroller modules and the whole system were designed to run in the laboratory only and no special attention was paid to flight environmental requirements. The environmental and EMC-requirements of the F-18 and Hawk pod made the hardware design of all subsystems challenging. Especially the vibration caused problems when a multiboard design is used. Damages and malfunctions caused by vibration were subcomponent level, not electrical component level ones: board-to-board connector, power module to printed circuit board (PCB), etc. The individual electrical components (integrated circuits, resistors, transformers, etc.) are mainly so lightweight that their mount to the PCB is lasting. For that manner, the vibration level is anyway far from the level causing internal damages to electrical components. EMC was also an issue in both pods: the level of conducted emissions exceeded the standard (MIL-STC-461E/CE102) in both pods. However, in both cases the emission level was reduced to acceptable level by adding a filter to the power feed. Concluding, the system modules have sufficiently been improved for flight-testing.

2.1.4 Data analysis and Data fusion (WE1123)

This work element gives an overview of different data analysis methods that can be used for SHM techniques (Ref. 2). Data analysis - or signal processing - methods are essential to any generic SHM system to extract features from different types of sensors and to translate this information into a diagnosis of the presence (yes/no detection) and characterisation (type, location, dimensions and severity) of damage. The selection of a signal processing technique is dependent on the specific SHM application and the specific data type.

Basic steps in signal processing for a SHM system include:

- Data pre-processing.
  - Smoothing / noise reduction (filtering, fitting, averaging).
  - Data compression / dimensionality reduction.
- Data analysis.
  - Time-domain (statistical parameter analysis, time series models).
  - Frequency domain (Fourier transform, Hilbert transform).
  - Time-frequency domain (short time Fourier transform, Cohen distribution, Hilbert-Huang transform).
  - Time-scale domain (wavelet analysis).
- Data post-processing.
  - Pattern recognition (neural networks, feature extraction/selection).

- Data fusion (multi-sensor architecture).

This table gives an overview of the applicability of data analysis methods for the different SHM techniques:

Data analysis method		SHM technique				
		AE	FBG	LW	SWISS	SG
Time domain analysis	Statistical parameter	++	+	+	++	+
	Time-series	0	0	0	++	0
Frequency domain analysis	Statistical parameter	+	++	++	+	++
	Fourier transform	+	+	++	++	+
	Hilbert transform	+	+	++	++	+
Time-frequency analysis	Short-time Fourier transform	+	++	+	++	+
	Cohen distribution	+	+	+	++	+
	Hilbert-Huang	+	+	++	0	+
Time-scale analysis	Wavelet transform	++	+	++	++	++
Learning techniques	Neural network	+	+	0	0	+
	Data Fusion	+	+	+	++	+
0 - less applicable, + - applicable, ++ - well applicable						

The individual data analysis methods of different sensing techniques needed improvement and have been improved significantly. Until now, it was not possible to work on data fusion. However, work on data fusion should certainly be done in a future project to make optimum use of the available data to enhance the reliability of inspection (increasing the POD and reducing the number of false calls).

2.1.5 Data Presentation (WE1124)

In this project a Graphical User Interface (GUI) by means of a Notebook System has been developed by (NIRAS) DEMEX in order to present damage data and more to the maintenance personnel. The GUI has been used during the ground tests and the flight tests of F-18 and Hawk aircraft.

In three levels information is given about the health status of the system and the structure to the user (Ref. 10): level 1 gives an indication about the status of the system (by means of lights), level 2 gives an indication about the health status of the structure (whether or not a damage or damage growth has been detected) and level 3 gives a graphical presentation of the damage (type, location and dimension). In level 3, also the detailed results of each individual sensing technique, graphs, images etc. can be obtained.

Fokker Services has investigated the possibility of using original design/production (3D) drawings for the presentation of the damage on the monitored structural part. This with the aim to give an as real as possible picture to the maintenance personnel.

Investigation showed that, due to the great amount of 3D CAD (CAM) file formats that aircraft manufacturers use for their aircraft structural drawings and presentations, it is impossible to write a common interface in

Labview to cope with all OEM structural drawings. Therefore, a solution would be to make an inventory of converters with one file format as output, for which only one interface with Labview should be created. Most programming in Labview is done in C/C++, so therefore the “to c” converters may be of most interest for creating a standard interface in Labview and use converters for the different industry standard 3D model formats.

Risø Ground Test (Ref. 22)

The notebook program could not be installed on a Risø laptop; therefore, the system was accessed via a DEMEX supplied computer on which the GUI program was pre-installed. This system was used only to connect to the network and download data for analysis elsewhere (directly by the sensor suppliers and by the notebook program integrated evaluation tool). Occasionally, it was not possible to make a notebook connection to the network, and this necessitated a direct FTP from the Central Computer data directory. None of the higher function data evaluation tools of the GUI was used during the ground test.

Because during the ground test not all systems were running simultaneously it was not possible to correlate the readings of the different sub-systems with the lab controlled loading. The change from testing all sub-systems in parallel (one common test set-up) to testing the sub-systems in series (separately) meant that the lab personnel had to cope with at least four individual set-ups during the workshop. To handle this change, the notebook system configuration files had to be drawn from scratch by DEMEX.

During the ground test, the notebook system was connected to the Central Computer (CC) for a considerable amount of time during data download after each test sequence. It became clear that for a full operational system there is a need for a quicker download speed. This is a requirement, which pinpoints that the amount of data gathered by the different measurement sub-systems should be reduced to a minimum. Furthermore, the interaction between the CC and the notebook system should be optimized. A possibility could be to use an interchangeable data storage medium onboard, in which case the time consuming data transfer procedure would be minimized/eliminated. Furthermore, it became clear that there is a need for storing (and presenting) only data sequences where sensor malfunctions or damage registrations occur.

Hawk Flight Test (Ref. 23)

According to the BAE partners there has been no problems using the program. The overall feedback is of a quick user-friendly program, which has shown no signs of breakdown during the test. This is in respect of the fact that the program was mainly used for quick and safe data transfers from the onboard equipment to the laptop. From earlier tests, the program as a whole has been useful, accompanied with suggestions to improvements.

F18 Flight Test (Ref. 24)

The DEMEX GUI software has operated smoothly during the tests. However, there was no need for making many inspections and relatively few people have used the system.

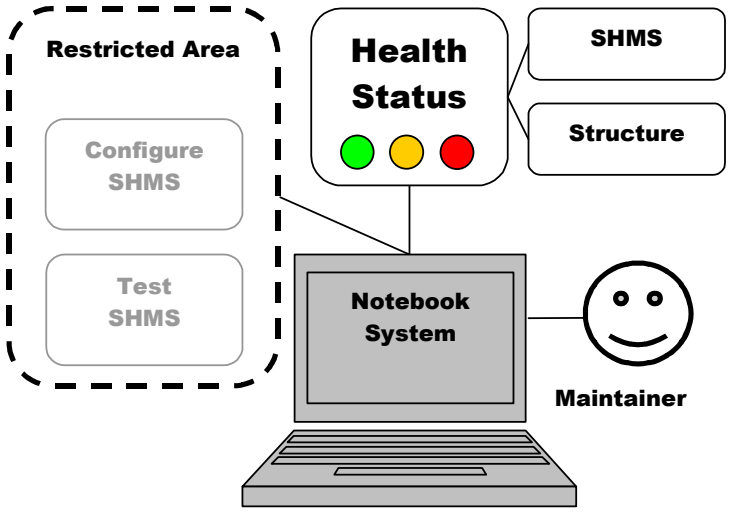
Not all the indications of the software were in harmony with the measured strains. The reason for this turned out to be different interpretations of the definitions. This minor non-uniformity can be easily corrected from the Demex or AHMOS-HW-SGSS unit software.

Questionnaire

After the development of the GUI, Fokker Services and DEMEX evaluated the system with the end-users (maintenance personnel of the Royal Netherlands Air force and Fokker Services). The end users were quite pleased with the GUI, especially with the Level 3 information, if fully developed.

After the completion of the AHMOS II WP2 tests, DEMEX sent a questionnaire to the users of the GUI notebook during the Risø ground tests, Hawk and F-18 flight tests. From the results of the questionnaire the following can be concluded:

- The users were overall satisfied with the performance of the Notebook System.
- The notebook system has primarily been applied for data download and secondarily for an overall health status check; i.e. applications that already from the design phase were meant for the “ordinary” user/maintainer (Level 1 and 2).
- Level 3 facilities, information on damage location and extent have - except for the F-18 test - not been used.
- None of the end-users has used the notebook system *configuration* facility during the test period. The fact, that the configuration task has been left with DEMEX whenever needed, indicates that it is too big a responsibility to give to even super-users. Due to the potential huge consequences, regarding health status misinformation if configuration is done improperly this feature should therefore be restricted as indicated in the figure below.



Conclusion

The GUI notebook has primarily been used to check the level 1 and level 2 status. Damage visualization at level 3 has not been used. The GUI notebook was used however to download the level 3 data from the central computer. This download in its current form takes too long for practical use in an operational environment. The use of an onboard interchangeable data storage medium has been proposed. Another solution would be to transfer only relevant data sequences.

The end-users during the AHMOS II tests are not fully representative for the end-user that will operate the SHM system in the future. During the AHMOS II tests, a verification of the level 3 data on a low level was necessary, also for building confidence in the system.

The creation of the required setup files takes a high level of expertise and was done by the supplier of the GUI notebook (DEMEX).

2.2 Ground tests to prove diversity in application of damage detection systems (WE1.2)

The purpose of the ground tests is to extend the test experience for potential monitoring tasks, to broaden the knowledge on feasibility of integrated damage detection techniques for a variety of platforms or components under practical conditions (Ref. 11).

2.2.1 Wing Full Scale test (WE1210)

The test part has been successfully manufactured. At least 25 of the FBGs are operative after the co-bonding of the test part. Due to delays, the structural test is scheduled for the 3rd/4th week of November 2007. The executive summary of this report will be included in an appendix to this report.

2.2.2 EF Slat fatigue test (WE1220, WE1290 and WE12A0)

The scope of the activities in these work elements can be summarized as follows (Ref. 12, 13, 14 and 15):

- Definition of the FBGS locations to be monitored.
- Description of the test load introduction system.
- Definition of the fatigue spectrum.
- Checking of the structure integrity.
- Fatigue measurements.
- Recording and processing of the measurements.
- Conclusions.

The FBGS have been located in areas where high strain levels are expected. The tracks and actuator cutout areas have been selected since a high stress level is expected in these areas due to the hole concentration effects. A continuous data recording has been performed during the fatigue test development. This dynamic data capture will be used to obtain the real fatigue sequences, cycle-by-cycle, at the FBGS locations.

These fatigue sequences have been developed in terms of strains at the FBGS locations, but it can easily be converted into stress sequences applying Hooke's Law. These stress sequences could be used directly to obtain the cumulative damage information at the FBGS locations.

The objective of fatigue tests is to monitor the behavior of the structure under the acting fatigue loads. Therefore, it is necessary to do inspections during the fatigue test to check that the structure is free of cracks. It is well known that in the case of the appearance of a crack in the structure, this crack causes changes in the load paths in the area surrounding to this crack. Therefore, by checking if there are changes or not in the strain measurements in the instrumentations installed close to the critical locations could be used of the indication of a possible crack in this area. Both FBGS static data capture or/and standard strain gauge data could be used to check this structural integrity.

The executive summary of this report will be included in an appendix to this report.

2.2.3 Marine Trial with AE (WE1230)

To be able to extract an AE response due to a change in structural state from the normal, legitimate structural response it is essential to gain knowledge about the AE (background) profile under normal operational conditions. The objective with the AE marine trial has therefore been to demonstrate that it is possible to generate an AE profile that varies with and is significant to the vessels operating environment (Ref. 30 & 31).

The AE measurements were carried out with a portable, dual channel AE system, Pocket AE equipped with two R15a AE sensors. The system records an extensive number of AE Hit parameters at every signal exceeding a pre-selected AE Hit threshold value, including Peak Amplitude, Energy and Duration. The system was chosen for these initial trials/investigations due to its all round ability to provide common AE parameters, but it would not be suitable as a permanently mounted system. A final full operational and permanently mounted marine SHM application should be tough, clever and cheap (simple).

During an eight-hour sail with a Danish Navy Standard Flex 300 vessel AE measurements were successfully taken against the vessels' composite hull while the marine vessel was operated at various speeds and maneuvers.

It is concluded from the marine trial measurements that the AE profile varies with the operating environment and furthermore with the measurement location (hull section), which indicates that it is possible to "map" the AE (background) profile of a vessel. This observation suggests that is possible to identify structural damage through an "exception analysis", i.e. changes in the AE profile.

Two generations of passive AE sensors have been developed and tested. The second generation AE sensor, while being completely minimized in terms of cost, seems to give a very good representation of the acoustic energy in a structure.

2.2.4 Landing Gear attachment Upper fuselage (WE1240)

C27 Platform vibration level simulation test applied on the FOBG instrumentation to verify the correct functionality of FOBG instrumentation before applying in flight on C27 Platform (Ref. 11).
Validation tests results about the crossing inboard/outboard of FOBG sensors through the C27 platform upper fuselage forward wing trap door. The critical point of this application is the ingress of the 4 external (outboard) FOBG inside the aircraft (inboard) in order to connect these sensors to the optical instrumentation; the FOBG crossing happens through the upper fuselage forward wing trap door.

The executive summary of this report will be included in an appendix to this report.

2.2.5 Embedding trials for FBGS (WE1250)

These trials deal with the manufacturing of carbon fiber reinforced epoxy specimens to assess the viability of FBGS monitoring technology for composite materials structures (Ref. 16). The aim of such an assessment is threefold:
1. To know how the insertion of FO sensors affects characteristic mechanical properties of host material.
2. To estimate the variation of FO performance through the evaluation of the characteristic 'K' coefficient, that converts wavelength units to deformation (or other) units for embedded sensors submitted to different type of efforts and for different material conditions in a temperature range that is representative for aeronautical structures in service.
3. To check if the entire interface of the optical fiber from the laminate egress to the optical connector can resist habitual fatigue and vibration envelopes in aeronautical environments.

All these three aims have been evaluated by the accomplishment of 'test matrixes' within the AHMOS II project. It could be seen that in all the different types of specimens, the used embedding techniques gave good results and the optical fibers are operative after the manufacturing of the host material. In the special case of the ruggedized specimens it could be seen that the embedded optical sensors and the fiber optic interface with its optical connector survived all the fatigue, vibration and acceleration conditions that simulates operative loads of military fighter aircraft.

2.2.6 Trial on instrumentation practicability of SWISS (WE1260)

SWISS Imaging Ultrasound sensors have been applied permanently to a selection of two hidden damage susceptible hot spot areas of a complex weapon system structure section (Ref. 17). Difficulties in the practicability of the instrumentation have been identified and overcome and sufficient quality and reliability of the installed sensors have been proven.

Fatigue tests have been conducted with the result that no false alarms occurred, as was confirmed by later conventional inspection.

Future improvements should address the ease of installation and the reliability of sensor bond for various materials (such as composite, aluminum, titanium and steel). Furthermore, real applications would require reliable means of over-seal, practical means of connecting cables with sensors and to ground-interface connectors at low weight and reduced cost (miniaturization!).

2.3 Flight test trials CASA (WE1.3)

No results were received. Preparational work is reported in ref. 18 and 19.

The executive summary of this report will be included in an appendix to this report.

2.4 Flight test trials Alenia (WE1.4)

No results were received.

The executive summary of this report will be included in an appendix to this report.

3 FLIGHT TEST PATH (WP2)

To demonstrate the technological maturity of a prototype integrated structural health monitoring system under operational conditions two flight test programmes have been executed (Ref. 20). A limited damage simulation was included in these flight tests to demonstrate the functional performance and the reliability of the SHMS under fast jet flight conditions for those sensing techniques that have to operate during flight.

One SHMS was installed on a pod of a Hawk test bed aircraft of BAE Systems (WE 2.5 "Flight Demonstration Hawk") and one on a pod of a F-18 aircraft of FiAF (WE 2.6 "Flight Demonstration F18"). The SHM systems were operated similar to a realistic scenario. The Hawk test bed was intended to offer the possibility to deeply investigate and control the flight test activities, but for a limited number of flights. The F-18 aircraft was planned to be exposed to independent in-service operation, but for a significantly larger period of flights.

Because the limited damage simulation in the flight test programmes was not deemed suitable to demonstrate practicability and applicability in terms of functional performance, a ground test (WE 2.4 “Ground Test Demonstration”) with realistic structural tests was performed to prove the damage detection and monitoring function for realistic structural forms on subcomponent level. Several simultaneously operated structural tests then allowed to demonstrate the complete SHM for a set of realistic monitoring tasks.

3.1 Preparational Ground tests (WE2.4)

During the ground tests at Risø, several independently but simultaneously operated sub component structural tests were performed during which the complete system with all sensing techniques was monitoring the damage development (Ref. 21 and 22).

The focus of these tests was on both **damage detection** (compare system output to actual damage evolution) and **system operation.**

3.1.1 Damage Detection

Sub-component and test definitions

Sub-component 1a (tensile test):
A large metal riveted panel with some structural detail
Description: <1.5mm thick, 1m^2 Aluminium
Sensor type(s): AE and SGI
Damage form: **Cracking at the rivets**

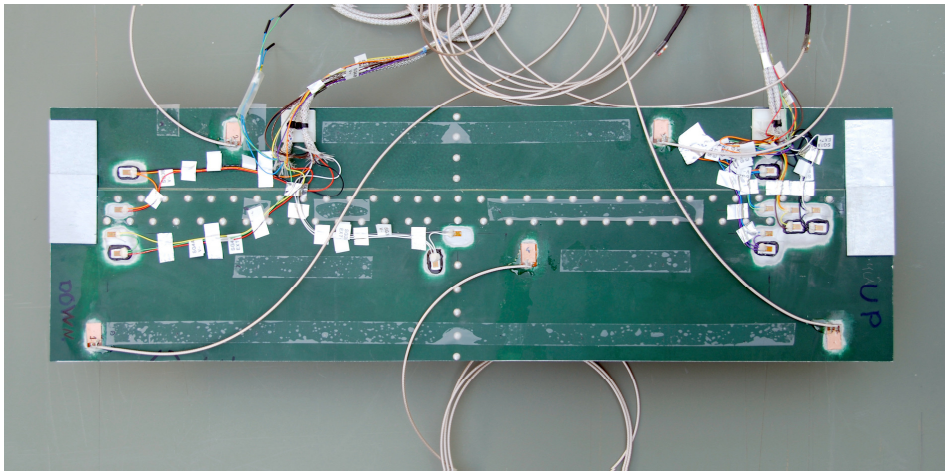
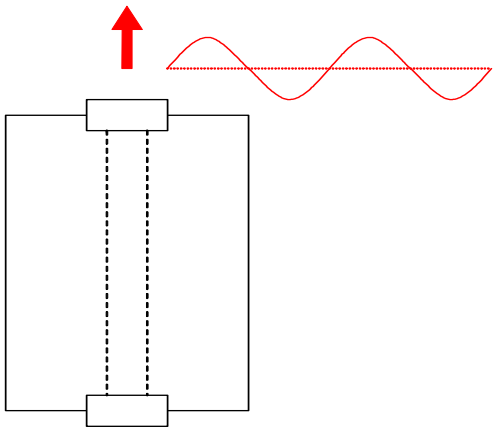


Figure 2: Showing the fully instrumented sub-component 1a

Instrumentation of sub-component 1a consisted of seven SGI sensors and five AE sensors. Figure 2 shows the overall distribution of sensors on the finished sub-component.

Test specifications for sub-component 1a

Mean load	Initial load level of 2kN Ultimate load level of 22kN
Amplitude	+/- 0.5kN
Fatigue	1 Hz



Sub-component 1b (peel test):

A large metal panel with bonded stringers

Description: <1.5mm thick, 1m^2 Aluminium

Sensor type(s): AE, FO, Lamb Wave and SGI

Damage form: **stiffener debonding**

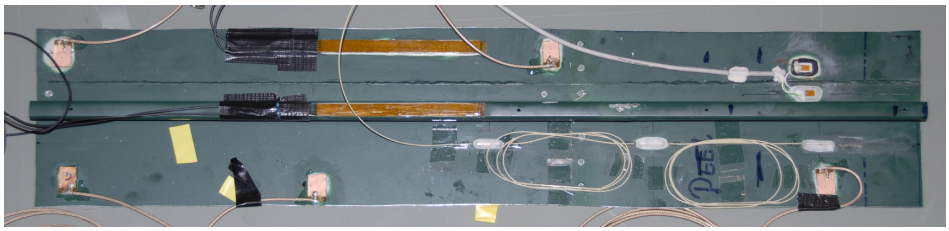
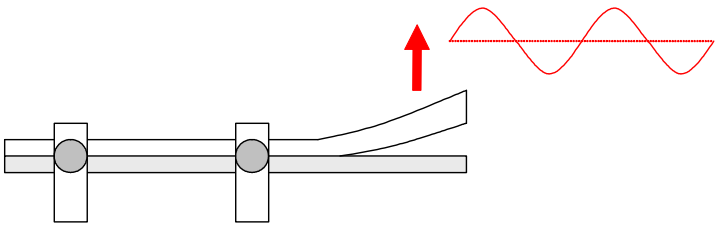


Figure 3: Showing the fully instrumented sub-component 1b

Instrumentation of sub-component 1b consisted of a single SGI sensor, five AE sensors, two FO strain sensors, and a lamb wave sensor. Figure 3 shows the overall distribution of sensors on the finished sub-component.

Test specifications for sub-component 1b

Mean load applied	300-600 N
Displacement Amplitude	0.15mm - 0.50mm
Frequency	1Hz



Sub-component 2 (four point bend test):

A CRFP panel stiffened by a bonded CRFP top-hat stiffener

Description: Quasi-isotropic CFRP 1m^2 panel

Sensor type(s): Lamb Wave, AE, and FO

Damage form: Disbonded stringer

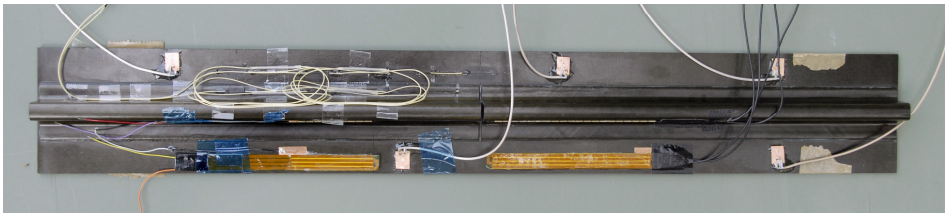
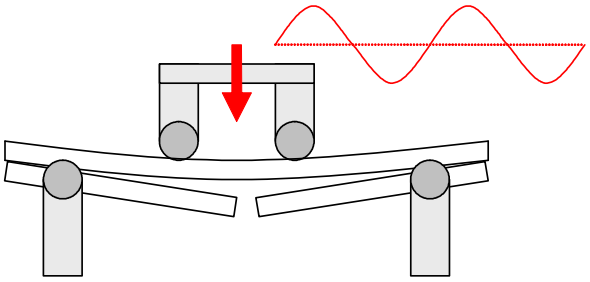


Figure 4: Showing the fully instrumented sub-component 2

Instrumentation of sub-component 2 consisted of five AE sensors, two FO strain sensors, and two lamb wave sensors. Figure 4 shows the overall distribution of sensors on the finished sub-component.

Test specifications for sub-component 2

Mean load applied	200-540 N
Displacement Amplitude	0.25mm – 0.75mm
Frequency	1Hz



3.1.2 System Operation

Network task

Prior to deploying the system for the ground test, the main network task was to assemble the full SHMS and test its' function. This task was led by Emmecon and supported by NLR (Central computer) and DEMEX (Notebook), with input from each of the sensor module suppliers. This task has successfully been accomplished.

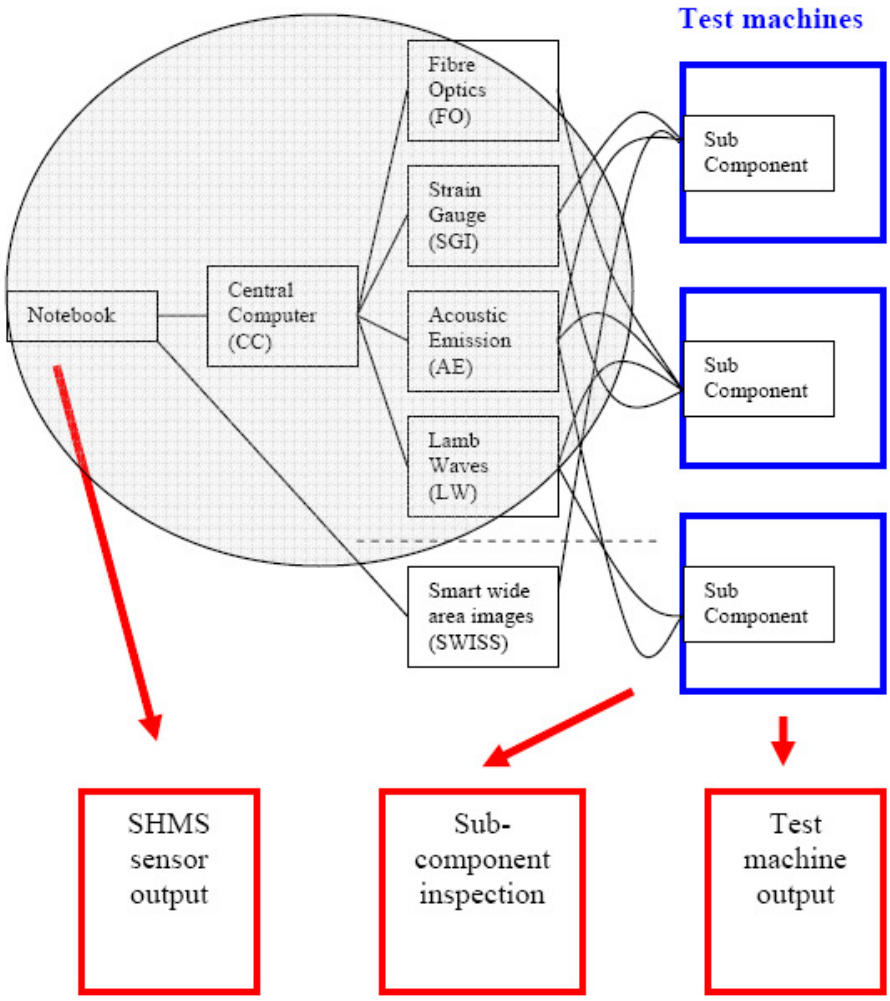


Figure 5: Diagram showing the AHMOS SHMS network, the test components and the data output from the Ground Test Demonstration

In the schematic diagram, the Central Computer Subsystem (CCSS) connected to each of the four on-line measurement subsystems: Fibre Optic (FOSS), Strain gauge (SGSS), Acoustic Emission (AESS) and Lamb

Wave (LWSS). These subsystems are all connected via an Ethernet switch. The AHMOS Notebook can also be connected to this network in order to download and interpret the sensor data collected by the Central Computer. Each of the four on-line sub-systems receives data from sensors attached to one, two, or three sub-components, as they are loaded in the test machines. The sensor data is analyzed and transferred to the Central Computer for later retrieval by the Notebook.
In addition to the on-line systems, there is the SWISS sub-system. This is an off-line measurement system that generates output once each test cycle is completed (while the aircraft is “on the ground”). The notebook connects directly to the SWISS SS to receive this data output.
The data generated during the Ground Test consists of the complete sensor output received by the AHMOS Notebook, the fatigue loading data from the test machines, and the visual inspections carried out on the three sub-components.
In addition to the working SHMS, a status monitor was included with the Central computer in order to provide a live indication of the status of the system throughout the ground test.

Notebook task

The objectives of the Notebook task in the Ground tests included supporting the network working group during set-up of the SHMS, demonstrating the primary functionality of the notebook in connecting and downloading the SHMS data gathered and stored in the Central Computer, and instructing Risø personnel to be able to operate the notebook hardware during the ground testing.
A manual was prepared specifically for the ground tests defining the AHMOSII SHMS notebook system. Detailed information about the Ground test Notebook system is contained in reference 28. This manual also defines the terms used in classifying returned damage for each sensor sub-system.

3.1.3 Ground test results

Notebook system

The Ground test was the first time all sub-systems were connected and collecting real data. Because not all of the systems were running simultaneously it was not possible to correlate the readings of the different sub-systems with the lab controlled loading.

Data analysis / output summary from the ground test

The change from testing all sub-systems in parallel (one common test set-up) to testing the sub-systems in series (separately) meant that the lab personnel had to cope with at least four individual set-ups during the workshop. To handle this change, the notebook system configuration files had to be drawn from scratch by DEMEX.

Hardware/software issues highlighted as a result of the workshop and/or ground test

During the ground test, the notebook system had to be connected to the central computer for a considerable amount of time for data downloading after each test sequence. For a full operational system, there is need for a quicker download speed. This can be e.g. accomplished by reducing the amount of data gathered by the different measurement sub-systems to a minimum. Furthermore, the interaction between the central computer and the notebook system should be optimized. A possibility could be to use an interchangeable data storage medium onboard, in which case the time consuming data transfer procedure can be minimized/eliminated.

Changes made because of the experiences during the workshop and/or ground test

Some optimization regarding the download speed of the system was programmed after the workshop. Furthermore, it became clear that there is a need for storing (and presenting) only data sequences where sensor malfunctions or damage registrations occur.

Development of the system readiness because of the workshop/ground test

At Risø, the AHMOS system reached a stage where it was for the first time possible to run the notebook system on non-simulated data. The download part of the notebook system was proven to work and fulfilled its purpose during the workshop. The other features of the notebook system were not addressed/tested, and therefore the readiness of these parts was not advanced during the workshop.

Central Computer

Hardware/software issues highlighted as a result of the workshop and/or ground test

One by one, the sensor systems were integrated with the Central Computer. Apart from some minor network issues, like cabling and duplicate IP addresses, the integration of the Central Computer with the strain gauge, fiber optical, and lamb wave sensor systems was successful. During the workshop, it was not possible to establish a network connection with the acoustic emission sensor. The problem was identified and verification of the solution was postponed to a later time. Data exchange with the notebook system was also verified and worked as expected. The Central Computer web interface proved a useful tool for online verification of level 1/2 sensor data.

Changes made because of the experiences during the workshop and/or ground test

No changes were required in the Central Computer hardware and software because of the experiences during the workshop. Network and system parameters are stored in a configuration file and they can be easily adapted to changes in network topology or sensor system behavior.

Development of the system readiness because of the workshop/ground test

The integration of the Central Computer with the AHMOS II system components on network and data exchange level was successful. Most of the network issues were solved during the workshop and the remaining matters were closed during the follow-up meeting at QinetiQ.

After the workshop no major issues were left that could block successful integration of the AHMOS II system components.

Strain Gauge

Data analysis / output summary from the ground test

The SGSS operated as planned and was successfully re-tuned by Risø.

Conclusions concerning the sub-component 1a (the tensile rivet test; 7 SG channels):

The anticipated failure mode (rivet hole cracking) was not achieved. Instead, the failure occurred around the lower grip region. The seven SG channels were however instrumented to capture cracking from rivet holes. Therefore, no results on damage detection capability.

Conclusions concerning the sub-component 1b (the peel test; 1 SG channel):

The anticipated failure mode (peeling) was achieved. The SG was working as anticipated to indicate there is damage for the anticipated failure mode (disbond).

Hardware/software issues highlighted as a result of the workshop and/or ground test

SGSS hardware used at Risø was the same, which was later, used in F18 and Hawk- test benches, no issues identified. In addition, the same software was later used in flying test benches, in Hawk-POD with minor modifications to support specimen characteristics. SGSS hardware and software functioned satisfactorily.

Development of the system readiness because of the workshop/ground test

The system itself worked as planned and the minor network problems were solved later.

The damage detection capability of the Strain Gauge system is summarised in the table below:

Specimen	Number of sensors	Damage Detected During Test [1, 2]	Damage Properties	
			Extent	Location
Composite Disbond	7	No[4]	No[4]	No[3,4]
Bonded Metallic Peel	1	Yes	No	Yes [3]

Notes:

1. All methods of damage detection using strain gauges (Fibre Optic or Electrical) require prior knowledge about what kind of damage is likely to occur and the expected location.
2. Post processing is included in the run time firmware of the Strain Gauge system.
3. The number of sensors and the spacing between them determines the accuracy of the location.
4. The anticipated failure mode (rivet hole cracking) was not achieved.

Lamb waves

General comments on the workshop and ground test and data analysis / output summary from the ground test

The LW system operated flawlessly on setup and during the first few hours of operation. It then developed an overheating problem. Several factors contributed to this problem. Firstly, the heat sinks for the transmitter power amplifiers were enclosed within the unit and not connected to the walls of the box, causing heat to build up inside. Secondly, the transmitter inhibit line which was designed to switch off the transmitter amplifiers temporarily during the receive phase was not activated by the control software. Thus, the transmitters were running continuously. As overheating did not occur when operating with the box lid removed, it was agreed that ground testing would continue without the box lid in place and that the overheating problem would be rectified after completion of the tests.

The composite Test Sample 2 was first tested in a four-point bend designed to cause disbonding of the stringer. Throughout the test, the LW system correctly transmitted both Level-2 and Level-3 data over the Ethernet network to the Central Computer (CC). Level-2 data took the form of a transmission parameter, an integer in the range 1 – 100 indicating the normalised transmission amplitude across the bonded joint and indirectly the extent of disbond, whilst the Level-3 data comprised the received waveforms, which were transmitted at a rate of approximately three per second. Initially, the normalised transmission amplitude was stable at 100 % +/- 3 % until the disbond entered the region monitored by the LW system when it began to fall, as the disbond progressed.

When the normalised transmission amplitude fell below the 85% threshold, damage was reported to the CC. The 85% damage threshold was chosen to represent an ‘Amber’ damage warning where the majority of the bond was intact but damage had been detected.

When the normalised transmission amplitude eventually fell below the 50% threshold, critical damage was reported to the CC. The 50% damage threshold was chosen to represent a ‘Red’ damage level where the disbond had reached a critical level. When reaching the Red, or critical, damage level, the Level-2 damage was reported as 255, as specified in the AHMOS II NETWORK AND COMMUNICATION SPECIFICATION.

The metallic specimen Test Sample 1b was subjected to a peel test in a tensile test machine. At intervals during the test, the point of tensile load application was adjusted by moving it to different positions along the stringer.

The test was carried out over a period of eight days, during which the LW system correctly transmitted both Level-2 and Level-3 data over the Ethernet network to the CC. Finally, the disbond extended to the region of stringer monitored by the LW system when, once again, the system immediately indicated the damage through the falling transmission amplitude. Waveforms from the test were also successfully stored over the network. Once again, when the normalized transmission amplitude fell below the 85% threshold, damage was reported to the CC. The 85% damage threshold was chosen to represent an *Amber* damage warning where the majority of the bond was intact but damage had been detected. When *Amber* damage had been detected, the damage field of the SAMH header was set. Level-2 damage continued to be transmitted whilst in the *Amber* damage state. When the normalized transmission amplitude eventually fell below the 50% threshold, critical damage was reported to the CC.
Thus, at the conclusion of the Ground Test, the LW sub-system had demonstrated disbond detection on both CFC and aluminum-alloy specimens.

Hardware/software issues highlighted as a result of the workshop and/or ground test

The following hardware and software issues were encountered in the course of the workshop:

- The analogue board of the LWS experienced overheating problems, which were temporarily mitigated by operating the LWS with the lid removed from the LWS enclosure.
- Minor inconsistencies with reporting the state of the LWS were observed and rectified.
- Movement of the LWS into the test hall caused a patch lead to become unsoldered from the analogue circuit board. This obviously has implications for any vibration testing.
- Significant problems were encountered with transferring FPGA programs to the flash RAM of the logic board. This resulted in substantial delays, and raises questions about the reliability of the current logic board. It was possible that the overheating of the LWS contributed to this.
- Significant delays were encountered due to the need to modify the FPGA software for each new time delay.
- Only a limited range of transmit and receive gains are currently available, and no filtering was available. This was the result of deviations from the original design and the selection of incorrect components. On the receiver amplifier this problem was mitigated by fitting a variable resistor, however only one transmitter gain was available, which seriously compromised the signal-to-noise ratio. It was not possible to mitigate the problems with the filtering.

Changes made because of the experiences during the workshop and/or ground test and development of the system readiness because of the workshop/ground test

Since the Ground Test, before flight-testing, all of the outstanding problems highlighted above were addressed and largely resolved. Improvements to the digital control software improved the downloading of FPGA programs to the flash RAM, and changes to the analogue gain control were implemented. To overcome the problem of transceiver overheating, the two output power amplifiers were moved to a position mounted on the transceiver

casing where heat could be dissipated in the case wall. More importantly, the control software was modified to utilize the power amplifier inhibit line, radically reducing their duty cycle and consequently their heat output.
The reason for failure of the first sensor installed on the carbon composite specimen was investigated. One previous similar example of sensor failure had been encountered during testing. This sensor was first examined and electrical continuity tests carried out, but no fault was identified. The sensor was then disassembled and the electromechanical coupling coefficient of the piezoelectric layer was measured and found to be normal. Ultimately, no clear explanation for the failure could be found, though it was conjectured that the sensor bonding could have been the cause.
These modifications were essential to the successful performance of the system throughout the subsequent flight-testing.

The damage detection capability of the Lamb Wave system is summarised in the table below:

Specimen	Number of sensors	Damage Detected?		Damage Properties	
		During Test	Post processing	Extent	Location
Composite Disbond	2	Yes	Yes	Yes [1]	Yes [2]
Bonded Metallic Peel	2	Yes	Yes	Yes [1]	Yes [2]

Notes:
1. The indicated damage extent was verified by visual and NDT measurements.
2. The system was configured to monitor a specified bond and the location of disbonding was known a-priori.

Acoustic Emission

The BAE Systems acoustic emission system was used in the ground tests at Risø and the Hawk pod flight test. The flight tests in the Hawk under wing pod provided a realistic environment for the system but imposed limitations on the test structure and duration. The ground test at Risø provided more realistic test structures but took place in a relatively benign environment.
The ground test was performed approximately half way through the AHMOS II program. Thus elements of the acoustic emission (AE) system, both hardware and software were still under development. For instance, Emmecon's signal processing board was developed in two phases. This allowed other system components to be developed without limiting its final functionality. The second phase was delivered later on in the program. It was not available for the ground tests at Risø. Thus, these tests were performed with the first phase device. Despite the use of interim rather than final versions of equipment and software, the system used at Risø was a good functional representation of the final devices destined for flight trial. The results from the Risø trials increased confidence in the overall system approach adopted for the AE system and decreased risk for the subsequent flight trials.

Description of tests and main results

This section describes data captured during the AHMOS ground tests at Risø in Denmark. The acoustic emission system recorded data from two test structures as damage was grown in them. The first structure tested was a carbon fiber skin co-bonded to a top hat stiffener. The stiffener was cut width-ways across its centre and the panel was loaded to encourage the bond to fail at the point where the stiffener was cut.
The second specimen was a riveted metallic structure put under load to induce the growth of metallic cracks.
Each specimen carried multiple sensors (e.g. strain gauge, fiber optic, Lamb wave etc.) from other AHMOS partners
The response of the AE system was checked before testing began by making a pattern of pencil lead breaks on both structures. The lead breaks (Hsu-Nielson test) simulate acoustic emission. This process is to ensure that the sensors were functioning correctly. It also allowed the speed of sound to be determined by recording differences in time of arrival of the lead break signals to reach each of the sensors. This timing information was used as calibration data for the AE event location algorithm.
Specimen testing took place over a two-week period. As only one AE system was available, the coupons were tested in sequence.

Examination of the AE waveform data gathered during the ground test revealed periodic interference picked up by the system. The source of this signal was not known at the time of the ground test. While this low level interference did seriously impede the acoustic emission system its elimination would improve the system's signal / noise performance.
The interference signal was eventually traced to the switched mode power supply. A minor modification to the circuit removed the interference.
Removing the interference signal also allowed the sensor signal gain to be increased enhancing the overall sensitivity.
Further shortcomings were observed with the AE system Built-In-Test facility. The acoustic emission system was designed with a self- testing facility, which uses the ability of the sensor to also be used as sound generators. One sensor is used to generate a simulated acoustic emission, which can then be detected by the other sensors. Thus, the system can determine if a sensor is functioning correctly. The self-test facility failed to function correctly during the ground test and as result; design modifications were made which proved successful on subsequent trials (including the Hawk flight trials)

The Risø ground tests served as a dress rehearsal for later flight tests of the AE system. The tests increased confidence of the overall system capability and highlighted some issues that could then be corrected. As such, the whole exercise reduced the risk for the final flight test programme.
The tests at Risø demonstrated particularly well the AE system's ability to detect damage in a failing composite bonded joint. The key features of these results are:

- Detection of multi-site damage originating from damage growth either side of the cut stiffener.
- By tracking, the clustering of events concentrated at the active crack faces, the progression and hence extent of disbond could be measured.

These composite disbond results are a valuable supplement to the overall evaluation of the AHMOS AE system and complement the evaluation results obtained during the flight trials which focused on a different form of damage detection: i.e. metallic crack detection.

Results from the riveted metallic specimen were not so conclusive mainly because the specimen failed in an unexpected fashion. Instead of damage occurring along the stiffener, the specimen failed at the load input point near one end. The positioning of sensors on the specimen meant that this region was not well monitored. Despite this, subsequent (post trial) analysis of the data yielded a location map with a cluster of events close to the crack albeit with a low statistical significance. This demonstrates some ability of the acoustic emission system to find damage in unexpected locations.

The issues discovered with interference and the built-in-test facility allowed improvements to the system to be made, which would not necessarily have occurred without the Risø trials.

The damage detection capability of the Acoustic Emission system is summarised in the table below:

Specimen	Number of sensors	Damage Detected?		Damage Properties	
		During Test	Post processing	Extent	Location
Composite Disbond	5	Not attempted	Yes	Yes (by tracking point of disbond)	Yes
Bonded Metallic Peel	5	Not attempted	Yes	No	Yes

Fibre optic

Data analysis / output summary from the ground test

Strain measurements were made on the bonded composite and bonded metallic subcomponents. There was no hardware, network of other interruptions to the data. Changes in the strain signals correlated well with damage events noticed during the test period.

The interrogator was configured to output data at the maximum rate possible, i.e., 8 sensors on each of 4 channels. Where less than 8 sensors were present on a channel, the rest of the spaces was to be filled with zeros.

Hardware/software issues highlighted as a result of the workshop and/or ground test

Optical parts of 4-channel instrument were assembled using COTS 1 x 2 splitters cascaded into a 1 x 4 arrangement and fitted in a standard splice cassette. Assembly was fiddly and the bare fibers exiting the cassette were vulnerable.

Periodic variation in the noise of data files, also reproduced in 'null' data (where the interrogator expects a sensor but none is connected). Spikes repeat every 64 points.

The noise levels varied from sensor to sensor. Some were near to our ideal level of 2 micro strain but many were much higher, around 20 micro strain.

The samples were instrumented with single FBG, which were then spliced together. The excess fiber was coiled and taped in position on the sample. While this was an easy, flexible method, it was, as expected a little untidy in that there was quite a lot of excess fiber to tidy up, approx. 500 mm for each pair of sensors.

Changes made because of the experiences during the workshop and/or ground test

Optics for flight instrument to be made from components with 900 mm protected fibers wired in place on a flat glass-phenolic PCB-type board for ease of assembly and handling. Optics also to be potted with silicone resin.

Future 4-channel instruments to be made with a custom 1 x 4 splitter.

Periodic spikes traced to an overflow error and corrected.

Output was limited to 2 sensors on one channel to reduce file sizes for the flight tests.

Some improvements were made to the signal processing which led to a reduction in the noise level for the flight tests. (Subsequent work has demonstrated that we can reliably achieve 5 micro strain resolutions and 2 micro strains are possible with further improvements).

No splices to be used in the flight coupon sensors. It was decided to use an array of 2 FBG rather than separate ones and to terminate this array directly into a connector.

Based on the experience gained processing the ground test data, LabView programs were written to process, check and display the flight test data, making the analysis much more efficient.

Development of the system readiness because of the workshop/ground test

We were greatly reassured by the successful integration of a working fiber-optic system into the AHMOS II system. Useful data was recorded and its analysis suggested a few improvements, some of which could be made in the Hawk flight test hardware and some of which were implemented in later versions of the hardware.

The damage detection capability of the Fibre Optic Strain gauge system is summarised in the table below:

Specimen	Number of sensors	Damage Detected [1] ?		Damage Properties	
		During Test [2]	Post processing	Extent	Location
Composite Disbond	4	Not attempted	Yes	No	Yes [3]

Specimen	Number of sensors	Damage Detected [1] ?		Damage Properties	
		During Test [2]	Post processing	Extent	Location
Bonded Metallic Peel	3	Not attempted	Yes	No	Yes [3]

Notes:
1. All methods of damage detection using strain gauges (Fibre Optic or Electrical) require prior knowledge about what kind of damage is likely to occur and the expected location.
2. The algorithms used for post processing can be implemented in the firmware of the Fibre Optic Interrogator to facilitate in-test detection.
3. The number of sensors and the spacing between them determines the accuracy of the location.

3.1.4 User comments

According to the Risø personnel involved in the ground testing, this prototype system did not (yet) display the level of integration, robustness, development or completeness intended in the final system. Examples of this lack include the necessity for unique software to connect directly with each sub-system in turn, the fragility of the communications network, the lack of facilities in the de jure interface, the lack of local data handling, etc.
The sub-component testing did not take place simultaneously, with the combined SHMS capable of detecting all damage types of interest. Due to the strong need for individual suppliers to validate their particular sub-system, meant the focus of the Ground Test changed from being a trial of a system comprising several damage sensor types, to being a test of various sensor sub-systems that shared a common data storage and download tool.

Network

Occasionally the network would become inaccessible and it was necessary to power cycle all the components and let the system reboot. The network environment was not robust and problems occurred if sub-systems (and other IP addresses) were disappearing and reappearing on the network. It was necessary to maintain the strict IP allocations in order to have a moderately stable network.

Central Computer

The Central Computer appeared well advanced in terms of hardware development.
The status monitor provided for use during Ground Test turned out to be vital, supplying “live” information of the composition of the network, the state of the system, and the operational condition of each sub-system. It was also the preferred control interface for effecting system mode changes.
The amount of data transferred to the Central Computer (especially by the Fibre Optic sub-system) seemed to be excessive and necessitated very long download times after loading periods.
Unexpected power outages (due to network inaccessibility for example) and data download without first changing operating modes could result in corrupted or improperly “closed/truncated” data files.

The Central Computer higher functionality with respect to configuration files, data directories, and log file access, etc. was not integrated with the user interface (Notebook) requiring a direct connection to make any changes.

Notebook

The notebook program was not successfully installed on a Risø laptop, and the system was accessed via a DEMEX supplied computer with the GUI program pre-installed. This system was used only to connect to the network and download data for analysis elsewhere (directly by the sensor suppliers and by the Notebook program integrated evaluation tool). Occasionally it was not possible to make a Notebook connection to the network, and this necessitated a direct FTP from the Central Computer data directory. None of the higher function data evaluation tools was used during the ground test.

SGSS

The SGSS appeared very well advanced in terms of hardware development. In addition, this sub-system included a local LED “status indication” display for the eight sensor channels (similar to the live status indication provided for all the sub-systems by the Central Computer status monitor).
It was possible for the 8-channel SGSS to monitor different sub-components (structural sections) that were being tested simultaneously. However, it was noted that the user was required to manually set “warning” and “damage” limits via direct connection to the sub-system and using unique software tools. Also noted was the fact that any changes in loading condition must also be reflected in a change to the user input limits, in order to continue to obtain good damage information from the sub-system. Furthermore, the SG sensors are vulnerable to “zero-drift” if the sub-component is placed in an unloaded state or handled for whatever reason, requiring manual connection/correction again to ensure channels are still giving valid data.
The manual supplied to assist in using the SG interrogator was excellent, and after being guided through the set-up once, it was then a simple (if time consuming) process to subsequently tune the channels.

Lamb Wave

The Lamb Wave module appeared to be the least developed hardware prototype used during the Ground Tests, and required the most technician attention during the workshop to prepare it for the testing. During the Ground Test however, this sub-system performed very well and supplied the most useful information to the status monitor allowing a good correlation between the damage growth and the sensor response to be displayed “live” during the testing.
The Lamb Wave sub-system higher functionality, with respect to configuration files for different structural material and tests, was not integrated with the user interface (Notebook) and required a direct connection to be made to the module with software tools provided by the sensor supplier.

SWISS

Unfortunately, it was not possible to integrate the SWISS sub-system during the workshop, and the hurried fatigue testing of sub-component 3 finally resulted in static failure, instead of damage growth. However, during cycling the ultimate self-test function of the imaging system worked: reflections from the specimen boundary have been repeatedly localized as a stable means of function prove, until when the arrays started to de-bond as the data showed, while it was not optically visible in the test rig. Pushing the installation mechanically then revealed de-bond. Nevertheless, the arrays were still working and have been reinstalled with an improved process of bonding. Finally, the arrays survived further cycling, but finally also the arrays have been broken by the static crack that occurred at about 10.000 microstrain. In summary, the tests did not give the expected good results, apart from highlighting the importance of a correct sensor bonding procedure. It was also noted that the SWISS system is operated entirely separately from the rest of the SHMS

Fibre Optic

The fibre optic hardware used in the Ground Test was not the system intended for use in the final SHMS. Off all the sensor sub-systems, the FOSS required the least attention from Risø during the Ground Test. It provided no information to the Central Computer status monitor beyond indicating its presence on or absence from the network. However it was very noticeable during data downloads as the FOSS flooded the CC (and Notebook) with high information content “level 3” data continuously, regardless of the state of the sub-components instrumented.

Acoustic Emission

The AESS module appeared well advanced in terms of hardware development. The acoustic emission sub-systems higher functionality with respect to configuration files for different structural materials and sensor distributions was not integrated with the user interface (Notebook) and required a direct connection to be made to the module with software tools provided by the sensor supplier.
During the Ground Test, the AESS displayed an occasional “sensor damaged” warnings on the Central Computer status monitor, these warnings were inaccurate and were generated by an automatic sub-system diagnostic routine.

3.2 Hawk flight test (WE2.5)

BAE Systems primary aim for WE2.5 of the AHMOS II programme (ERG103.015) was to demonstrate for the first time, successful, operation of integrated automated damage detection systems, in- flight, aboard a BAE Systems Hawk aircraft (Ref. 23). A further aim was to demonstrate the viability of selected damage detection technologies to a Technology Readiness Level of seven (TRL7). Following on from the successful trial of an automated damage detection system in RTP 3.20 AHMOS, the consortium focused on adapting the technology to the Hawk flying test bed demonstrator programme within ERG 103.015.

The system was designed to monitor damage growth on two structural items located (metallic crack growth and metallic disbond) inside an underwing Hawk instrument pod during flight. The system will function as part of an integrated SHM architecture comprising a number of SHM technologies from project partners. Ground-based trials of the technology, utilizing other partners' facilities, will underpin and supplement the flight trials. The success of this programme will provide evidence for all stakeholders that an integrated, automated damage detection SHM system is proven to TRL7.

The down-selected sensor technologies were:
- Acoustic Emission, BAE Systems ATC
- Strain Gauge, Emmecon
- Fibre Optics, Smart Fibres
- SWISS, KT Systems
- Lamb Wave, QinetiQ

Also contained within the Hawk pod system, was a communication Ethernet Hub Switch to allow the sensor equipment boxes and the central computer, utilized for data storage, to communicate with each other. The central computer data could then be downloaded to the laptop both for analysis and to generate a real-time presentation of structural health provided via the Graphical User Interface (GUI).

3.2.1 Acoustic Emission

The acoustic emission systems has demonstrated the ability to detect the growth of cracks in aluminum allow structure in flight aboard a fast military jet while undergoing unrestricted flight maneuvers at a range of altitudes. Moreover, the trials have indicated a promising resilience to 'false positives' as demonstrated by clear delineation in systems response to damaged and undamaged specimens.

The acoustic emission system operated successfully throughout the flight tests. Very weak acoustic emission events were detected in a noisy, high vibration, high acceleration, and high- altitude environment. Acoustic emission events were also detected despite high levels of electrical interference from other on-board systems.

The processes put in place to screen out spurious signals were only partially successful necessitating some post analysis of data. Examination of the spurious signals that were not rejected will help us to refine our screening process. This work is currently ongoing.

The damage detection capability of the Acoustic Emission system is summarised in the table below:

Specimen	Number of sensors	Damage Detected?		Damage Properties	
		During Test	Post processing	Extent	Location
Metallic, fully instrumented	3	Not attempted	Yes	No	Yes (localized to flight specimen)
Metallic, partly instrumented	3	Not attempted	Yes	No	Yes (localized to flight specimen)

3.2.2 Strain Gauge

The SGSS developed in AHMOS II has proven to be rigid and reliable in extreme conditions by mechanical and electrical construction and by software. Emmecon's software platform used also in acoustic emission and lamb-wave systems has proven to be flexible and reliable. SGSS is versatile and could be modified for loads monitoring based life assessment with software modifications.

The detection of damage based on strain measuring requires solid understanding and/or modeling of the structure. The sensors have to be located so that the strain caused by the normal loads and changes in strain caused by the damages can be isolated. In ground and flying test benches of the AHMOS II, the cracks were reliably captured with SGSS in others but not in Hawk-pod.

The damage detection capability of the Strain Gauge system is summarised in the table below:

Specimen	Number of sensors	Damage Detected During Test [1,2]	Damage Properties	
			Extent	Location
Metallic, fully instrumented	3	No [3]	No [3]	No [3]
Metallic, partly instrumented	n.a.	Not attempted	No	No

Notes:
1. All methods of damage detection using strain gauges (Fibre Optic or Electrical) require prior knowledge about what kind of damage is likely to occur and the expected location.
2. Post processing is included in the run time firmware of the Strain Gauge system.

3. Damage tolerance parameters of the damage assessment algorithm were set too tight which caused false alarms. If specimen used in Hawk pod had been tested in laboratory in shaker with representative spectrum, the Hawk test would most likely had been successful, too.

3.2.3 Fibre Optics

The interrogator hardware was qualified for flight worthiness in time for the flight programme. Flight-testing was successful and delivered high quality data.

There were no significant failures, however there were problems obtaining the desired FO connectors in time for the pod sensor install, the lower spec alternatives caused some problems, which meant we had to actively align connectors whenever new test specimens were installed. The testing and analysis required to successfully implement damage detection algorithms were under-estimated at the outset of the project. Meaning that the equipment has not completely fulfilled its potential in this aspect.

The damage detection capability of the Fibre Optic Strain gauge system is summarised in the table below:

Specimen	Number of sensors	Damage Detected [1] ?		Damage Properties	
		During Test [2]	Post processing	Extent	Location
Metallic, fully instrumented	2	Not attempted	No [3]	No	No
Metallic, partly instrumented	1	Not attempted	Yes [4]	No	No

Notes:
1. All methods of damage detection using strain gauges (Fibre Optic or Electrical) require prior knowledge about what kind of damage is likely to occur and the expected location.
2. There is no reason why the algorithms used for post processing could not now be implemented in the firmware of the Fibre Optic Interrogator to facilitate in-test detection.
3. Method attempted during post processing was to measure differences in strain fields of two sensors at different distances from the area of crack growth. We learnt that to successfully apply this method would likely require more than two sensors.
4. Method used during post processing was to measure changes in the resonant frequency of the specimen when excited by aircraft maneuvers.

3.2.4 SWISS

Complementary to the other successful damage detection techniques the imaging ultrasound technique and the associated SWISS equipment has been used to support the objective of this project to “Demonstrate operational prototype SHMS based on mature enough sensing techniques by flight test demonstration supported by independent full scale on-ground damage detection tests” (ref. contract ERG103.015).

For this purpose, pre-integrated broadband ultrasound matrix arrays have been installed to a metallic specimen in the Hawk test bed mini-lab to detect and localise damage that would emerge as result of vibrational loads. A crack of length 6 ± 2 mm has been detected, localised and quantified.

The pre-integrated arrays allow quick and practical installation, avoiding soldering or similar on a weapon system platform's structural item. To qualify for flight tests the given type of installation has undergone an airworthiness test programme, with only minor deviations, which were acceptable. An improved surface preparation method guarantees extraordinary life times.

Throughout this programme the weight of cabling issue remained, because better alternatives were not available and if, they are for industrial applications only (like the analogue bus system of the KTS220).

The off-board equipment, necessary for operating the sensors installed on board has been miniaturised considerably (from one cubic metre to portable), but not to the extent that would be technologically possible (as has been implemented for a KTS220) because the risk that necessary electronic components could fail was considered to be too high without prior analysis of maturity. Compared to AHMOS II technology the KTS220 integrates substantial parts of electronics with transducers and thereby eliminates the cabling issue and improves the system performance: higher sensitivity due to lower noise, less cross-talk, reduced susceptibility to EMI.

In general permanently mounted imaging ultrasound arrays offer the same or better capabilities of ultrasound monitoring, but also a breakthrough in cost reduction. 112 channels have been used in the case here involving tremendous costs – not for the sensor, but for the wiring. Industrial applications (KTS220) offer between 16 to up to 1000 channels and more. Every added channel costs only 50€ so that adding redundancy to the monitoring sensor network becomes affordable.

Since natural echoes, such as holes, corners or boundaries offer an ultimate self-test capability a false alarm rate of 0% has been demonstrated here and a theoretical maximum of 3% estimated thereof. A partial degradation, non-functioning or loss of some elements in a multi-element network is to some extent backed-up by the remainder of the sensor-network and does not imply that the hole system fails due to local impairments.

It seems reasonable, to also exploit the same technology to measure deformations in areas, where sensors cannot be placed (e.g. hidden corners), to detect plastic deformations or measure deformations on-line.

Future activities should address the need to specify actual monitoring tasks which possibly could replace existing visual, eddy-current, ultrasound or visual inspection, offering similar capabilities as NDI and requiring similar expertise, but eliminating the need for disassembly, re-assembly and rechecking. For these monitoring

needs, validations –similar to existing NDI – should be conducted by challenging industrial next generation versions of imaging ultrasound equipment for use on military platforms.

The damage detection capability of the SWISS system is summarised in the table below:

Specimen	Number of sensors	Damage Detected [3]		Damage Properties	
		During Test	Post processing	Extent	Location
Metallic, fully instrumented	112 in three groups	Never, by principle[1]	Yes [2]	Yes 6 mm	Yes

Notes:
1. Imaging Ultrasound with SWISS is an interval based inspection technique. Data is acquired during a test or at intervals. There from independent, the imaging process and subsequent interpretation of the data is done in a post-data-acquisition point in time and allows post-measurement choice of wave types and material parameters in contrast to conventional imaging equipment that requires selecting these parameters at the time of operation.
2. A crack of 6mm has been detected as the specimen was damaged after the last inspection interval. A 2 mm accuracy is given by the physics of the sensor system used here to detect a crack between 1 and 3 mm as requested. Previous inspections revealed only minor changes, which suggest that the damage was below 1 to 3 mm.
3. The damage has been found as a spatial increase (of about 6mm) of the original echo that resulted from the notch that was in the specimen. Whether this quantification is correct could not be checked yet, because other installations (strain gauges) cover the area of interest. In another hot spot area on the specimen (opposite side) it has not been as clear due to physical reasons, which seem reasonable and are documented in the report. The ultimate self-test capability (imaging of a given echo - the original notch) has been proven and a limited tolerance, if some individual sensor element channels fail has been demonstrated.

3.2.5 Lamb wave

The Lamb-wave system was applied to three specimens where it performed without false call throughout the flight test programme and successfully detected and tracked the disbonding in two of the specimens. It is considered that the performance of the Lamb-wave system would have provided sufficient evidence to support a Technology Readiness Level of 7 for this particular application to bondline monitoring, but that this must be reduced to 6 owing to the temperature-compensation issue.

The configuration of the trial SHM system isolated within an aircraft underwing pod proved highly successful. The Lamb-wave specimen design, together with the ability to specify the profile of each flight test, successfully enabled a disbond to be propagated within the short duration of a single sortie. The scheduling of the flight test programme was beyond the control of the AHMOS team and the success of the Lamb-wave flight testing relied heavily on the ability to quickly change specimens in the short turn-round servicing period between flights. However, the very close scheduling of flight tests meant that there was no time for data analysis or remedial action between flights following Flight 3. Project resources were sufficient for only three instrumented Lamb-

wave specimens and since the high-altitude flying was scheduled for Flight 7 the last specimen had to be preserved through Flights 5 and 6. No damage was induced in this final specimen and, since there was also insufficient time to repair the damaged temperature-compensation sensor, Flights 5, 6 and 7 provided neither damage detection nor temperature-compensation data, so their value in respect of the Lamb-wave system assessment was marginal. Further specimens and more time between flights could have circumvented these difficulties and provided greater benefit from flight-testing.

The damage detection capability of the Lamb Wave system is summarised in the table below:

Specimen	Number of sensors	Damage Detected [1] ?		Damage Properties	
		During Test [2]	Post processing	Extent	Location
Lamb-wave specimens (FL1)	2	Yes	Yes	No [1]	Yes [2]
Lamb-wave specimens (FL2)	2	Yes	Yes	No [1]	Yes [2]
Lamb wave specimens (FL3)	2	No [3]	No [3]	No [3]	No [3]

Notes:
1. The system was unable to determine the extent of disbond during flight owing to a problem with the temperature compensation scheme.
2. The system was configured to monitor a specified bond and the location of disbonding was known a-priori.
3. No damage was generated during flight-testing.

3.2.6 Graphical User Interface

According to the BAE partners there has been no problems using the program (Ref. 32). The overall feedback is of a quick user-friendly program, which has shown no signs of breakdown during the test. This is in respect of the fact, that the program mainly was used for quick and safe data transfers from the onboard equipment to the laptop. From earlier tests, the program as a whole has been useful, accompanied with suggestions to improvements.

3.2.7 Conclusion

It has been shown that SHM systems can function in an aviation environment. Seven flights were performed. Strain Gauge sensors and Swiss sensors flew only for two flights.

AE operated successfully during all flights. Damage was detected. Interference occurred from outside factors (overseal separation of SWISS sensor detected, presence of Fibre Optic, Strain Gauge and SWISS sensor increased dampening effect on the specimen, damage occurring not on specimen but elsewhere in the pod).

Strain Gauge controller successfully operated during all flights, functioned and detected damage when the sensors were installed. Sensor location is critical.

Fibre Optics successfully operated during all flights; damage was detected but not quantified. This requires further development of algorithms.

SWISS was installed on the first two flights. Damage was detected and quantified.

Lamb wave successfully operated during all flights. Damage was detected but not quantified due to a temperature-compensation algorithm that must be further developed.

3.3 F-18 flight test (WE2.6)

The purpose of the F-18 AHMOS-pod flight testing was (Ref. 24):

1. Test the operation of the strain gauge and SWISS systems in actual military aviation environment. Because of the nature of the systems (COTS components used, simplified ground testing etc.) and the test environment (severe conditions at the wing tip) it was possible that problems were encountered. In these cases, reasons for the problems and possible solutions to them were studied within the resources available for the project.
2. Test the capability of the systems to detect cracks in these circumstances. The fatigue test set-up has been extensively tested on the ground, so there was a relatively good prediction how and when the test specimens will crack. This is why the flight test was only used to show that the systems operate similarly compared to ground testing. Emergence of cracks was to be estimated comparing the ground test results, traffic light indications, strain measurements and SWISS sensor images. Also, it was planned, if necessary, to detect the cracks with other NDT methods.
3. Collect practical experience from the FiAF personnel of the operation of the systems. Because the nature of the flight-testing was development testing, not certification testing, no special operational requirements were set for the tested systems.

The F-18 AHMOS-pod, which is designed for the AHMOS-project, is a look-alike of the AIM-9 CATM missile, which is the training version of the AIM-9 Sidewinder air-to-air missile. Inside the AHMOS-pod, there are test

specimens equipped with strain gauges and SWISS sensors, equipment to load the specimens, AHMOS-HW-SGSS strain gauge measuring and analysis unit and data network.

The specimens were designed to have a fatigue life of approximately 100 hours, which was assumed to be roughly divided in 50 flight hours and 50 hours of activities when the electrical system is switched on but the aircraft is not flying (inspections, engine start-up, taxing etc.).

3.3.1 Strain Gauge

The operation of the AHMOS-HW-SGSS strain gauge measuring and analysis unit has been monitored using the traffic lights and the data recorded by the system. During the first five flights, monitoring was possible from the traffic lights as long as the aircraft started to taxi for take-off. During the first flight, just as the plane started to move, the traffic lights showed that the system fell down and started to reboot immediately. This was also visible from the recorded data. Based on the recorded data there is no other indication that the system has fallen down.

The damage detection capability of the Strain Gauge system is summarised in the table below:

Metallic, fully instrumented specimen no.	Number of sensors[3]	Number of channels[3]	Damage Detected During Test [1,2,3,5]		Damage Properties	
			LEFT	RIGHT	Extent	Location
25	4	2	No damage	Detected Damage,	No[4]	No[4]
26	4	2	Not detected damage	Detected Damage,	No[4]	No[4]
27	4	2	No damage	Not detected damage	No[4]	No[4]
28	4	2	Detected Damage,	Detected Damage,	No[4]	No[4]

Notes:
1. All methods of damage detection using strain gauges (Fibre Optic or Electrical) require prior knowledge about what kind of damage is likely to occur and the expected location.
2. Post processing is included in the run time firmware of the Strain Gauge system.
3. Each specimen is instrumented with four strain gages. Two upper side strain gages form a half bridge connected into one measuring channel of the SGSS. Two lower side strain gages form a half bridge connected into one measuring channel of the SGSS. Upper side LEFT and lower side LEFT strain gages are in same position but on opposite sides of the specimen. Upper side RIGHT and lower side RIGHT strain gages are in same position but on opposite sides of the specimen.
4. The number of sensors and the spacing between them determines the accuracy of the location.
5. [24, chapter 3.4.4]

3.3.2 SWISS

The hardware for making the SWISS system inspections were delivered to Patria in June and the software in July 2007, more than a year later than planned in the schedule. This is why the flight-testing was started without the system. The first attempts to carry out SWISS system inspections were done in August. However, the first inspection was succeeded in early December using other equipment than originally intended for the AHMOS project. This meant that no data was available from earlier inspections to be used as a reference, which would be necessary to detect and localize damage smaller than 2 to 3 mm.

The inspections done in early December were done only with SWISS sensors of an earlier generation, not with the next generation sensor. When making the inspections it was noticed that one sensor did not respond. The reason was found to be a faulty cable. Because the pod was disassembled it was possible to make the inspection using another sensor's cable.

The SWISS sensors were on test specimens 25, 26 and 27. In general, it seemed that the sensors had survived the flight-testing. The SWISS system inspections indicated that if there are cracks they are bigger in specimen 25 than in 27 because the ultrasound changes were very small. The image did not clearly indicate possible cracks or the artificial notches. The reasons for this are not yet understood. The changes identified by the SWISS sensors in the ultrasonic response indicate that the damage is very asymmetric, i.e. probably on one side only.

The results also indicate a possible debond of the sensor on specimen 26 because the changes in the ultrasound response were unexpectedly high - although a larger crack would be expected to result in a similar change. However, conventional NDT only reported small cracks. Only imaging could bring up further help to interpret the data (similar to Hawk tests), but first attempts did not result in a satisfying image. The sensor does not move and the bonding seems intact so it is possible that the debonding originates to the bonding process. No conclusions can be done of the status of this test specimen, because the changes are significantly larger than the changes found in 25 and 27.

The damage detection capability of the SWISS system is summarised in the table below:

Specimen	Number of sensors	Damage Detected [2]		Damage Properties	
		During Test	Post processing	Extent	Location
Metallic, fully instrumented	16 in one group	Never, by principle[1]	No [2]	No < 2 mm	Small changes near sensor

Specimen	Number of sensors	Damage Detected [2]		Damage Properties	
		During Test	Post processing	Extent	Location
Metallic, fully instrumented	16 in one group	Never, by principle[1]	No [2]	No < 2 mm	Small changes near sensor
Metallic, fully instrumented	16 in one group	Never, by principle[1]	Yes [2]	No, Large crack or debond or both	Large changes near sensor

Notes:
1. Imaging Ultrasound with SWISS is an interval based inspection technique. Data is acquired during a test or at intervals. There from independent, the imaging process and subsequent interpretation of the data is done in a post-data-acquisition point in time and allows post-measurement choice of wave types and material parameters in contrast to conventional imaging equipment that requires selecting these parameters at the time of operation.
2. A 2 mm accuracy is given by the physics of the sensor system used here to detect a crack between 1 and 3 mm as requested. Inspections revealed only minor changes, which suggest that the damage was below 1 to 3 mm.

3.3.3 Graphical User Interface

The DEMEX GUI software (Ref. 33) has operated smoothly during the tests. However, there has not been a need to make many inspections and relatively few people have used the system.
Not all the indications of the software were in harmony with the measured strains, because after flight thirteen the green light was shown for both sensor and structural health status. This was not logical for such a large change. The reason for this turned out to be different interpretations of the definitions. Because of this, the behaviour of the Demex software traffic lights and the pod traffic lights was not analogous. This minor non-uniformity can be easily corrected from the Demex or AHMOS-HW-SGSS unit software.

3.3.4 Conclusion

The Strain Gauge measuring and analysis unit operated normally during the flight-testing. The strains indicated the emergence of four of the six cracks found with traditional NDT methods.

The SWISS sensors survived the flight-testing and strain levels in the test specimens. The SWISS system did not detect the cracks with certainty because they were below 1,6 mm which is below detectability of the 2 MHz transducer.

Except for an EMI problem (interference on the cockpit audio system) on 3 out of 4 aircraft used, the system passed all tests. The EMI problem could not be resolved in the timeframe of this project because of the slow progress of the flight-testing.

3.4 Qualification Aspects (WE2.1)

3.4.1 Software qualification

Whenever a system is developed for commercial or military aircraft the safety of the crew and occupants is a factor in the development of the system. Airworthiness authorities established various procedures to qualify that the system meets the safety critical objectives.

At the highest level, the Authorities require that the aircraft is qualified and that the qualification includes all different systems. Within the systems, any implemented software must be qualified.

The qualification plan is the document that establishes the criticality of the system and its various components. This determines the level of design assurance required by the regulations. It also establishes the software approval levels as required by the software development standard RTCA Inc. DO-178B.

As part of the qualification process, the system safety assessment is used to determine and categorize the failure conditions and the criticality of a system. The objective is to identify requirements that will preclude or limit the effect of faults, and may result in fault detection and fault tolerance requirements being added.

The failure condition categories used by DO-178B are:

A. Catastrophic.
B. Hazardous/Severe-Major.
C. Major.
D. Minor.
E. No effect.

A DO-178B criticality level is assigned to the software under development based on the contribution that the software may make to potential failure conditions, as determined by the system safety assessment process.

Table 3.4.1 shows the relationship between the system safety definition and the software criticality level and how it relates to the verification objectives as defined by DO-178B section 6.4.4.2.

Table 3.4.1 DO-178B Software Criticality Levels

Software Criticality Level	**Definition**	**Associated Structural Coverage Level objectives (DO-178B 6.4.4.2)**
Level A	Software that could cause or contribute to the failure of the system resulting in a catastrophic failure condition.	Modified Condition/Decision Coverage, Decision Coverage & Statement Coverage
Level B	Software that could cause or contribute to the failure of the system resulting in a hazardous or severe-major failure condition.	Decision Coverage & Statement Coverage
Level C	Software that could cause or contribute to the failure of the system resulting in a major failure condition.	Statement Coverage
Level D	Software that could cause or contribute to the failure of the system resulting in a minor failure condition.	Not required
Level E	Software that could cause or contribute to the failure of the system resulting in no effect on the system.	Not required

The verification objectives for DO-178B are set in place to detect and report errors that may have been introduced during development processes. Software verification objectives are satisfied through a combination of reviews and analyses, the development of test cases and procedures, and the execution of those test procedures. Reviews and analyses provide an assessment of the accuracy, completeness, and verifiability of the software requirements, software architecture, and source code.

The Software Criticality Level of at least C should be considered at the commercial introduction of a SHMS in (military) aircraft. This means that Statement Coverage applies for the Structural Coverage Analyses Objective. Statement Coverage means that every statement in the program has been invoked at least once.

During software development in this project, however, the failure of the SHMS will not have any influence on the aircraft safety, which means that software criticality level E (refer to table 1) applies. We advise, however, to do software qualification for a limited part of the software as developed by the various partners during the project in order to experience the associated work.

3.4.2 Hardware qualification

During AHMOS II extensive amount of hardware qualification testing has been performed.

All the system parts that have been installed in the Hawk pod have successfully been tested on the ground (Ref. 29) and in flight either by suppliers or by BAE Systems.

All the system parts that have been installed in the F-18 pod have also been ground (Ref. 29) and flight-tested. Except for an EMI problem (interference on the cockpit audio system) on 3 out of 4 aircraft used, the system passed all tests. The EMI problem could not be resolved in the timeframe of this project because of the slow progress of the flight-testing.

All test results are documented in the Qualification Program Plan (Ref. 26).

4 TECHNOLOGICAL READINESS LEVEL OF SYSTEMS

Another task in WP3 is to include an overview of the Technology Readiness Level (TRL) of the different sensor techniques and sub-systems. All AHMOS II partners were invited to define their key system development(s) in the AHMOS II programme (e.g. AE on composite/metal structures, embedded/surface mounted FBG, Lamb wave, SGI, GUI, etc.) together with main the detection/research objective (impact damage, surface crack, sub-surface crack around fasteners, skin-stiffener debond, residual stress, chemical sensing, etc.), TRL rating, substantiation of the TRL (e.g. in cases where a relatively low TRL was caused by failure of other sub-systems), main advantages, main limitations, and future needs. The key systems can be systems developed and evaluated in laboratory environment, during ground tests (e.g. at Risø), and during the 4 flight tests in UK, Finland, Spain and Italy. Therefore, it can include research and development activities in both WP1 and WP2 of the AHMOS II project.

4.1 TRL Rating

GAO/NSIAD-99-162 Best Practices (Appendix 1) definition of TRL, which is presented in table 4.1, has been used (Ref. 25). The discussion between experts showed that the given definitions of TRL levels could be interpreted in various ways. Thus it has been rather difficult to agree on a unique TRL for some subsystem modules, meaning that an error of plus or minus 0.5 is still expected. Still this is a good indication of the overall TRL, which can range from one to nine.

Table 4.1 Definition of Technology Readiness Level (TRL)

Technology readiness level	**Description**
1. Basic principles observed and reported.	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties.
2. Technology concept and/or application formulated.	Invention begins. Once basic principles are observed, practical applications can be inverted. The application is speculative and there is no proof or detailed analysis to support the assumption. Examples are still limited to paper studies.
3. Analytical and experimental critical function and/or characteristics proof of concept.	Active research and development is initiated. This includes analytical studies and laboratory studies to physical validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4. Component and/or breadboard validation in laboratory environment.	Basic technological components are integrated to establish that the pieces will work together. This is relatively 'low fidelity' compared to the eventual system. Examples include integration of "ad hoc" hardware in a laboratory.

Technology readiness level	Description
5. Component and/or breadboard validation on relevant environment.	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so that the technology can be tested in a simulated environment. Examples include "high fidelity" laboratory integration of components.
6. System/subsystem model or prototype demonstration in a relevant environment.	Representative model or prototype system, which is well beyond the breadboard tested for TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high fidelity laboratory environment or in a simulated operational environment.
7. System prototype demonstration in an operational environment.	Prototype near or at planned operational system. Represents a major step from TRL 6, requiring the demonstration of an actual system prototype in an operation environment, such as in an aircraft, vehicle or space. Examples include testing the prototype in a test bed aircraft.
8. Actual system concept and "flight qualified' through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include development test and evaluation of the system in its intended weapon system to determine if it meets design specifications.
9. Actual system "flight proven" through successful mission operations.	Actual application of the technology in its final form and under mission conditions, such s those encountered in operational test and evaluation. In almost all cases, this is the end of the last 'bug fixing' aspects of true system development. Examples include using the system under operational mission conditions.

4.2 TRL Evaluation

The result of the inventory is given in table 4.2. The table shows that the TRL varies from value 3 (analytical and experimental critical function and/or characteristics proof of concept) to value 7 (system prototype demonstration in an operational environment). TRL 7 was reached for the AE (crack detection in metal structure), corrosion sensor, FBG (strain measurement), SGI and SWISS sensor systems. Also, the system network and modules, GUI and central computer were rated with a TRL 7. This is an appreciable improvement in comparison with the TRL values obtained in the predecessor project AHMOS I. In that project the maximum TRL value was only 5 (component and/or breadboard validation on relevant environment), reached for the surface mounted FBG and the SWISS system.

Table 4.2 AHMOS II System Evaluation

AHMOS partner	SHM System	Detection/research objective	TRL	Substantiation of TRL	Advantages	Limitations	Future needs
EADS-G / WIWEB	SWISS	Localisation of both defects and selected boundaries to check structural integrity at required confidence in hidden and/or uninstrumented areas. Covers otherwise called "phased array ultrasound" or similar techniques.	7	7: Hawk flight trials - Localisation of artificial defect (hole) - Repeatability of undamaged boundary (hole) Remark: TRL 7 applies to above determined test case and used implementation. Implementation readiness is by definition significantly lower. Significantly improved implementation concepts start at lower TRL (e.g. 3).	- Robust instrumentation - Retrofit - Low cost multiplexing - Comparable NDI needs - Potential to deal with unexpected damage evolution - Potential to detect as sensitive as existing NDI - Potential to merge with techniques that require similar hardware - Expert independent automatic offline multi-mode interrogation - Expert post-analysis on demand, without need for availability of platform - No on-board software changes necessary - Redundancy: even if some individual elements fail, the monitoring capability may not be affected	- Relative range-reduction for monitoring of non-linearities - Requires more acquisition time than NDI (~min,~h) - Requires built-in growth potential at time of retrofit (e.g. 28 channels, when only 11 are needed) to cover extended spots, conventionally covered by moving NDI - Only physical data evaluation. No empirical - Global material changes can only be detected if they result in a significant change of the scatter distribution	- Improvement of sensor material and structural miniature design (high technological risk) - Improvement of off-board electronics to exploit second breakthrough in range - Improve software to automate parameter selection - Alternative approach to currently known global (non NDI) monitoring concepts: requires elaboration of future case specifications in parallel to low TRL development
Alenia	FBG	Strain measurement	5	- Qualification test for on ground application - Flight test on C27	- Robustness - Multiplexing - EMC immunity	Point technology	Capability to monitor an entire area of a component
CIRA	FBG	Strain measurement	5		- Robustness - Multiplexing	No real weakness	- One-chip engineering
	FO, reflectometr. and LPG approach	Chemical sensing	6		- Sensitivity - Versatility depending on the material choice	- Packaging - Reliable interrogation systems	- Monitoring on selectable chemicals for specific applications

AHMOS partner	SHM System	Detection/research objective	TRL	Substantiation of TRL	Advantages	Limitations	Future needs
BAE Systems	AE	Crack in metal structures	7	Hawk flight trials of AE system	- Wide area coverage - No dependence on defining initial undamaged state - Less susceptible than UT based systems to sensor degradation (i.e. method depends largely on AE signal frequency characteristics rather than absolute signal magnitudes)	- Damage sizing difficult - Requires live load to 'activate' the acoustic emissions so that an on-line system is required	-Methodology for 'in service' use - In-service validation of data, confer conventional inspection methods
		Metal stringer disbond	6	Risø lab tests	As above	As above although continuous monitoring can plot progress of linear disbonds as they propagate hence some sizing possible	As above
		Composite stringer disbond	6	Risø ground tests and Joint lab tests with QinetiQ	As above	As above	As above
	Corrosion sensor	Indication likely occurrence of corrosion	7	Advanced lab trials plus other military aircraft trials outside of AHMOS	Needs no on-line instrumentation (passive witness sensor)	Assumes surrounding structure corrodes at the same rate as the sensor	In-service validation of data
QinetiQ	LW	Metal stringer disbond	6/7	System was successfully proven on the BAE Hawk flight test. LW system operated in flight for the duration of all of the flights and correctly classified damage to the specimens in real time	- Active system, can operate on ground - Can be configured for plug-in ground operation with reduced weight - Can be configured to detect other defect types - System does not require continuous operation to monitor the structure (can be employed on periodic basis) - Low cost of system; low cost & weight of sensors	- Resolution is dependent on the size of the sensor - Structurally specific - Requires a baseline of the initial undamaged structure	- Improved temp. compensation - Sensor robustness

AHMOS partner	SHM System	Detection/research objective	TRL	Substantiation of TRL	Advantages	Limitations	Future needs
		Composite stringer disbond	6	System was successfully proven on the Risø ground test. LW system operated without error for the duration of the test and correctly measured and classified damage of the specimen. Since the composite specimen was not flight tested, the TRL is lower than the Metal stringer disbond	As above	As above	As above
Smart Fibres	FBG	FBG strain measurement	7	Strain measurements made with FBG sensors during all 7 Hawk flight tests	- Strain/load measurements can enhance the capability of other SHM techniques - Sensors are small, immune to EMI, intrinsically safe and several can be multiplexed on a single optical fibre if desired - Cabling is lighter than copper cable and less is needed for a given number of sensors - Performance is as good as or better than comparable electrical strain gauges	- Interrogator currently has maximum temperature rating of 55 °C - Minimum bend radius of optical fibre may limit installation flexibility, but this can be worked around	- Active cooling of laser - Reduction in size and weight. Capability of flight-tested model was 18 FBG/kg. Current model is 27 FBG/kg, target is 50 FBG/kg. - Investigate implementation of sensors in bend-tolerant fibre (5 mm allowable bend radius)
		Crack in metal structures	N/A	Playback of data on ground revealed strain changes associated with crack growth. Algorithm to perform automatic detection was suggested but not implemented in Hawk flight tests. However, the hardware was flight-tested	See above	*A priori* knowledge of crack location required	- Study of optimal sensor placement for damage detection - Develop algorithm or process to help designer choose number and location of sensors - Investigate possibility of

AHMOS partner	SHM System	Detection/research objective	TRL	Substantiation of TRL	Advantages	Limitations	Future needs
		Metal stringer disbond	4/5	Disbond detected during Risø ground tests. System was a prototype, not ruggedised for flight, hence lower TRL (4 for interrogator and 5 for sensors)	See above	Disbond needs to be close to a sensor. Note that many sensors can be multiplexed on one fibre to allow that fibre to detect and track a significant length of disbond	combining strain/load measurements directly with another SHM technique to produce a composite damage indication
		Composite stringer disbond	4/5	See above	See above		
Airbus (S)	FBG based damage sensing on CFRP	Composite stringer disbond	4/5	Disbond detected during ground tests. System used is a standalone equipment	- Embedded optical path and sensors (high level of integration-protection) - Compatible with strain measurement systems - Strain/load measurements can enhance the capability of other SHM techniques - Sensors are small, immune to EMI, intrinsically safe and several can be multiplexed on a single optical fibre if desired - Cabling is lighter than copper cable and less is needed for a given number of sensors - Performance is as good as or better than comparable electrical strain gauges	- Demodulation system requires certain level of spectral measurement capability (secondary peak detection or full spectrum measurement capability), not required for strain measurement systems - Disbond needs to affect the bonding line area where the FBG is embedded. Note that many sensors can be multiplexed on one fibre to allow that fibre to detect and track a significant length of disbond	Improve optoelectronics and algorithms to reduce / avoid coupling of longitudinal/transverse and its effect on the signal to noise ratio
EADS-CASA	FBG bonded on metallic surface	- Strain/Stress measurement - Calculation fatigue life consumption - Load path failure	7	- Ground Test “EF-2000 Slat Fatigue Test” - Flight test trials on C101	- Multiplexing of several sensors per fibre - EMC immunity - Small size of sensors (allowing to monitor areas that actually can not been monitored with strain gauges) - Easy sensor installation in comparison with strain gauges	- Equipment needs auxiliary laptop - Use of FBG sensor to monitor temperature (due to the difficult uncoupling of load and temperature effects) - Fragility of the fibre (several loops of fibre were necessary to be installed in the Ground Test)	- Analysis new installation to use FBG sensors to monitor temperature - Temperature compensation - Comparison of FBG and strain gauge measurements - FBG sensors to monitor damages

AHMOS partner	SHM System	Detection/research objective	TRL	Substantiation of TRL	Advantages	Limitations	Future needs
INTA	FBG embedded in composites	Strain measurement	5	INTA Composite Material Department organization and facilities do not aim at reaching a higher TRL. The aim of INTA participation is to provide results and experiences so that Airbus España and/or EADS-CASA can go beyond in TRL	- Not susceptible to EMI - Size of sensors - No significant influence on host material properties - Reliability in extreme operative environment conditions -High robustness of the embedded sensors (including cables and connectors)	- Cross sensitivity of temperature/strain - Influence of temperature and humidity on strain sensitivity - Limited repeatability observed in acrylic-coated sensors (due to hysteresis after thermal cycling, minor problems due to humidity)	- Temperature compensation - Test campaigns on embedded sensors with other coating materials different from acrylic
NIRAS DEMEX	GUI	Development of GUI software for retrieving, joining and presenting the structural health status data to end user	7		- Movable 3D-illustration - Statistics - COTS, and price - User friendly - Adjustable to different sensors and flight types	- Off-board use only - Implementation of damage sizing	- Implementation of damage location and sizing algorithm - Upgrading of software speed
	AE – Marine trial	Zonal profiling inspection demo under normal operation	3	Proof-of-concept demo with commercial system only	SWE output correlated with location and operating environment	- COTS - Manual inspection only	- Further analytical and experimental function - Installation system development
Risø	AE – Anakron flight	AE activity output integrated with standard flight measurements	5		- Instant SWE output visible on flight controls - Hard landing assessment	Operating environment only	- Integrated system - Signal discrimination - Planer localisation
	AE - turbine	Continuous (12months+) zonal profiling under normal operation	6	Modified commercial system only	SWE profile history for the structures correlate with operating environment	- Exception analysis only - Zonal	- Planer localisation - Signal discrimination - Improved data integration
VTT	SGI	Crack in metal structures	7	- AHMOS-I (Hawk centre fuselage test) - Patria table tests - Hawk under wing pod flights - F-18 wingtip pod flights	- Proven technology - COTS support from multiple sources (component providers)	Limited detection range (structural “hot spots” and failure mechanisms must be known prior to installation)	
		Metal stringer disbond	7	- Risø ground test	See above	See above	

AHMOS partner	SHM System	Detection/research objective	TRL	Substantiation of TRL	Advantages	Limitations	Future needs
Emmecon	System network and modules		7	- WIWEB, Risø and QinetiQ lab tests - Hawk and F18 pod-tests	- Standard HW and communication interface (TCP/IP). Expansion of the network is PnP - Modules are "stand alone" and thus not continuously network dependent	Quality and mechanical layout of the commercial Ethernet switch is not good enough.	Electromechanical layout in most of the equipment
	SGI		7	- WIWEB, Risø, QinetiQ and Patria lab tests - Hawk and F18 pod-tests - Environmental tests (EMC, temp, pressure, vibration, shock)	- Rugged design - Stand alone operation with data storage - Suitable for loads monitoring - Multichannel (8)	Some obsolete components used	Electronics and enclosure redesign
NLR	Central computer	Data storage of SHM sensor systems	7	- Risø ground tests - Hawk flight tests	- On-board data storage - Web based real-time monitoring	- Use of COTS equipment	- Memory less sensitive to vibration
	EC sensor	Surface crack in metal structures	4	System only evaluated in laboratory environment	- Flexible sensor for radii	- Limited detection range (sensor size) - Temperature sensitivity	- Temperature compensation - Time monitoring capabilities of MultiScan (> 1 day)
		Sub-surface crack around fasteners	4	See above	- Sensitivity of crack detection	- Limited depth of penetration (about 3 mm) - Temperature sensitivity	

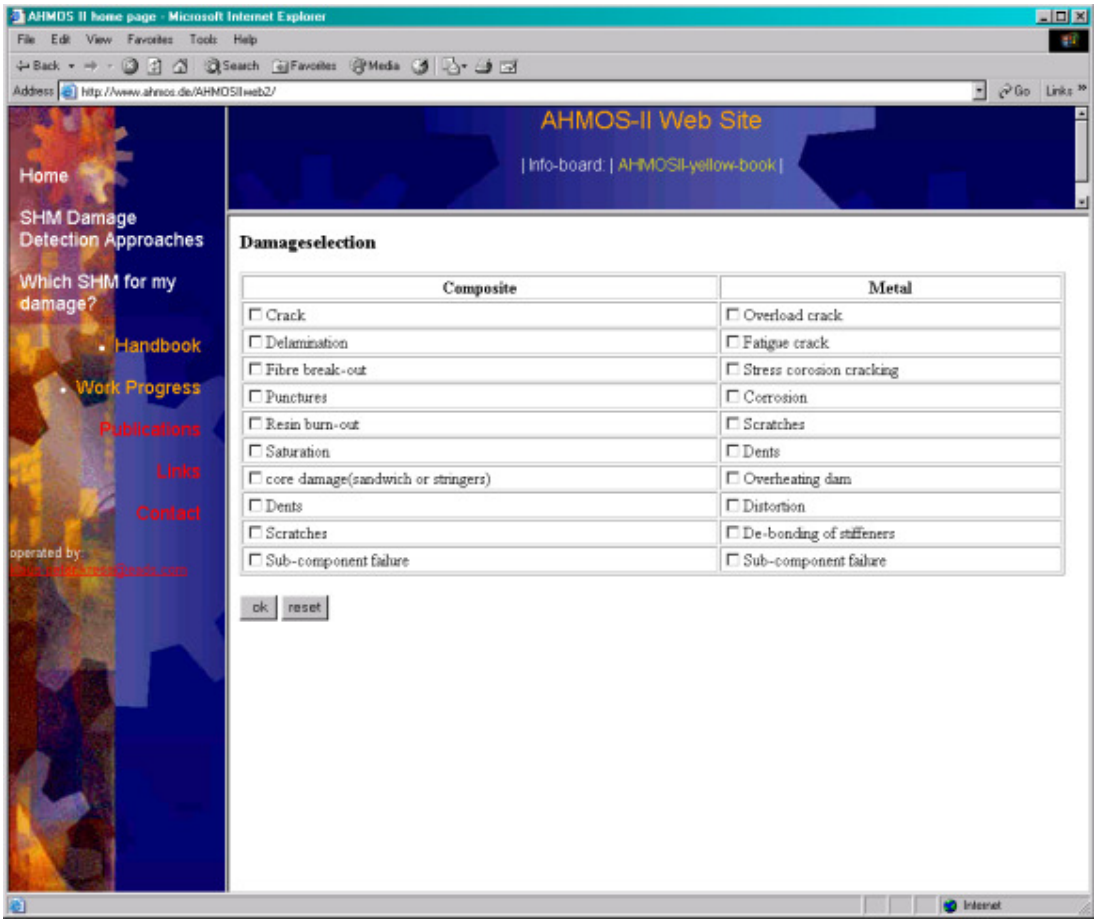
4.3 Conclusions

An overview of the Technology Readiness Level (TRL) of the different sensor techniques and sub-systems evaluated in the AHMOS II project is given. The TRL varies from value 3 to value 7. TRL 7 was reached for the AE (crack detection in metal structure), corrosion sensor, FBG (strain measurement), SGI and SWISS sensor systems. Also, the system network and modules, GUI and central computer were rated with a TRL 7.

The TRL values are considerably higher than those obtained in the predecessor project AHMOS I. In that project the maximum TRL value was only 5, reached for the surface mounted FBG and the SWISS system.

5 BENCHMARKING TOOL AND DECISION SUPPORT TOOL

A Java based tool has been developed and implemented in the AHMOS II website, see the figure below.



By selecting the material and the damage type that is to be detected, the tool gives an advice on suitable detection technologies.

6 IDENTIFICATION OF NEXT STEPS FOR EXPLOITATION AND IMPROVEMENTS

6.1 Introduction

In this chapter the next steps will be defined to facilitate the introduction of a SHM System on an aircraft, using the before mentioned results (achievements and failures) of the AHMOS II work. The following areas will be discussed in detail: sensor systems, system network and modules, damage presentation (graphical user interface) and qualification of the systems.

6.2 Sensor Systems

In AHMOS II, the following sensors have been tested during ground testing and or flight-testing: Acoustic Emission, SWISS, Strain Gauge, Fibre Optic Bragg Grating (FOBG), and Lamb Wave (LW).
Furthermore, theoretically or in laboratory testing the following sensors have been analyzed: eddy current array sensor, long period gratings (LPG's), corrosion sensor, and fibre optic sensor using a reflectometric approach.

6.2.1 Acoustic Emission (AE)

The AE detection technology is real-time. It is designed to operate while the platform is in service undergoing operational loads. Sensors are surface mounted. AE sensors have been used in ground testing as well as in the flight test with the Hawk.
Damage detection capability of the AE sensors has again been proven. The capability of damage localization and extent, which is potentially one of the major benefits of AE sensors, is however not yet proven. Due to the short period of testing, aspects such as the reliability, robustness could not sufficiently be challenged. Although, the AE sensors claim to be global sensors, meaning that they are capable of detecting damages in large areas, this has not been tested in this project. Initially, further developments for the in service use of this sensor should focus on "hot spot' monitoring.
The claimed Technology Readiness Level for this sensor is 7. Considering the achievements in AHMOS II this claim can be acknowledged. Nevertheless, many more tests in representative environments are necessary to bring this system to its final form for introduction. This can be achieved by extensive development and testing of complete systems in accurate operational conditions (ground and flight tests).

Further work is needed in the following areas:

- Proving 100% reliability of damage detection in the monitored area. This requires extensive testing and validation.
- Further development of damage localization capability.
- Further development of damage extent determination capability.
- Ground testing to prove robustness of the system.

- Further development of software to provide Level 3 damage presentation data to the Graphical User Interface.

6.2.2 SWISS

SWISS (Smart Wide area Imaging Sensor System) is based on ultrasound. In principle, it has the potential to detect all such damages (e.g. corrosion, cracks, delaminations etc.) that can be detected by ultrasound in conventional inspections. The self-test capability of sensor, sensor-coupling to metallic specimen after instrumentation and under in-service like conditions has been demonstrated. Also the known-good ultrasound response of known-good (healthy) structure has shown sufficient repeatability to serve as ultimate self-test of the system functioning. Damage has been detected when damage occurred. Localized damage (cracks) in the structure has been detected, localized and quantified. Depending on the specific installation and implementation, SWISS has demonstrated applications specific potential to deal with unexpected (non-lab-like) behavior of hot-spot areas. In summary, SWISS has been used on the ground and the flight tests with application specific success.

The sensors are surface mounted. The SWISS system is not a real time system, which means that the system is not active during the operation of the aircraft. Interrogation of the structure for damages is done on the ground only.

The claimed Technology Readiness Level for this sensor is 7 (“flight proven”). The same level of TRL does not apply to the prototype off-board equipment, since the technological lower criticality for off-board, off-line operated equipment demanded less allocation of resources within this project to the off-board hardware in favor of proving the robustness of on-board sensor instrumentation. Considering the achievements in AHMOS II an overall TRL 7 (including off-board hardware) could not be achieved. Nevertheless, many more tests in representative environments are necessary to bring this system to its final form for introduction. This can be achieved by extensive development and testing of complete systems in accurately defined monitoring tasks under operational conditions (ground and flight tests).

Further work is needed in the following areas:

- Proving 100% reliability of damage detection in the monitored area. This requires extensive testing and validation.
- Further development of automatic damage localization and interpretation capability.
- Further development of damage extent determination capability (more channels, but same weight & cost).
- Ground testing to prove robustness of the system (including off-board/on-board hardware).
- Further development of software to provide Level 3 damage presentation data to the Graphical User Interface.

6.2.3 Strain Gauges

The Strain Gauge technique can be used for damage detection in metallic aircraft structure. Strain Gauge sensors are surface mounted and are only suitable for monitoring known 'hot-spots'. Because of the limited coverage area of the strain gauges, the positioning of the sensors is extremely important. This requires a good knowledge of the structure to be monitored and its failure mechanism.
Although the Strain Gauge technique and system are on a quite high technology readiness level (TRL 7) still much more work is to be done with testing on the ground and in flight, in accurate operational conditions, in order to quantify the reliability of the system, probability of damage detection, etc.
The claimed Technology Readiness Level for this sensor is 7. Considering the achievements in AHMOS II this claim can be acknowledged. Nevertheless, many more tests in representative environments are necessary to bring this system to its final form for introduction. This can be achieved by extensive development and testing of complete systems in accurate operational conditions (ground and flight tests).

Further work is needed in the following areas:

- Proving 100% reliability of damage detection in the monitored area. This requires extensive testing and validation.
- Further development of damage extent determination capability.
- Further development of software to provide Level 3 damage presentation data to the Graphical User Interface.
- Wireless technology.

6.2.4 Fibre Optic Bragg Grating (FOBG)

The Structural Strain Variation monitoring technique by means of FOBG is real time. It is designed to operate with the platform in operation. FOBG sensors have the potential to detect delamination and debonding in composite material, cracks in metal structure, to do strain measurements and to do fatigue life consumption calculations. The FOBG sensors can be surface mounted as well as embedded in composite structures.
FOBG sensors have been tested on the ground tests at RISØ, on the Hawk flight-testing, on ground and flight-testing in Spain (EF-2000, C101) and Italy (C27).
The claimed Technology Readiness Level for this sensor varies from 4 to 7. Considering the achievements in AHMOS II these claims can be acknowledged. Many more tests in representative environments are necessary to bring this system to higher TRL's. This can be achieved by extensive development and testing of complete systems in accurate operational conditions (ground and flight tests).

Further work is needed in the following areas:

- Proving 100% reliability of damage detection in the monitored area. This requires extensive testing and validation.

- Ground testing to prove robustness of the system.
- Further development of software to provide Level 3 damage presentation data to the Graphical User Interface.
- Improve capability to monitor larger areas.
- Reduction in size and weight
- Improve bend radius of optical fiber or investigate the possibility of bend tolerant fiber
- Active cooling of laser
- Further improvement of optoelectronics and algorithms to reduce/avoid coupling effects.
- Temperature compensation.
- Coating materials

6.2.5 Lamb Wave

The capabilities of the Ultrasonic Guided Wave (Lamb Wave) system are limited to monitoring of the structural integrity of a region of structure local to the transducer. Therefore, this system is useful only to monitor 'hot-spots' for debonding of joints, cracks and possibly corrosion. The system requires to be specifically configured for each monitoring region with respect to both the defect type and structural acoustic properties. UGW sensors are surface mounted. This system has been used on the Risø ground testing and on the Hawk flight-testing. Test results show that the system has detected the debond, in real time, during flight-testing, without any false calls.

The claimed Technology Readiness Level for this sensor is 6. Considering the achievements in AHMOS II this claim can be acknowledged. Nevertheless, many more tests in representative environments are necessary to bring this system to its final form for introduction. This can be achieved by extensive development and testing of complete systems in accurate operational conditions (ground and flight tests).

Further work is needed in the following areas:

- Improvement of the robustness of the system.
- Further development of software to provide Level 3 damage presentation data to the Graphical User Interface.
- Improvement of the temperature compensation

6.2.6 Eddy current array sensor

The investigation showed that the high-frequency absolute sensor is suited for the detection of surface cracks located just beneath the sensor. This sensor is flexible and can be bent down to small radii; the sensor produces reliable EC signals for radii down to 7 mm. The low-frequency reflection ring sensor can be used for subsurface crack detection in riveted joint structures. The detectable crack length for this sensor depends on the inspection configuration, the depth of the defects and the test frequency. As a rough indication, defects from

about 8 mm at a depth up to 3 mm in lap joints of Glare 4B-0.4 material are detectable. Smaller defects (length < 6 mm) and defects at larger depth (depth > 4 mm) are not detectable anymore.
Both prototype sensors are sensitive to changes in ambient temperature. This should be considered (and compensated for) when performing SHM measurements at different temperature, for example during in-flight and on-ground conditions.

The feasibility and potential applicability of both EC sensor types for the local detection of cracks in metal aircraft structures has been demonstrated. However, much further work is needed. For example, it is recommended to increase the monitoring capabilities of the MultiScan equipment in order to use the system for practical SHM applications. The system should allow continuous operation for periods much longer than one day (main areas of attention are the acquisition rate and the cursor length in the strip chart display of the instrument). It is also recommended to evaluate the multi-sensor capability of the MultiScan equipment using a specified 16-channel switch box (in the present investigation only single sensor measurements were performed).

It is recommended to further investigate both the high-frequency absolute sensor and the low-frequency reflection ring sensor using different and realistic specimen configurations under fatigue testing. The actual limits of flexibility of the high-frequency absolute sensor should be investigated using specimens with smaller radii (< 7 mm). The low-frequency ring sensor should be further investigated for the detection of sub-surface corrosion in aluminum alloy structures.

TRL for this technique is correctly set at 4. Therefore, extensive further research and development is needed to become sufficiently mature to be used on aircraft.

6.2.7 Long period gratings (LPG's)

The investigation concludes that low cost, commercially available equipment (including a spectrometer with a wavelength resolution of 0.1 nm) based on HRI coated LPG's, can provide advanced chemical sensing for VOC's, gases, and liquid monitoring in light of the easy multiplexing capability and lower complexity compared to alternatives such as Plasmon resonance or waveguide sensors.

This basic research has shown the potential of LPG's for SHMS purposes. The claimed TRL 6 could not be acknowledged. TRL 4 is more appropriate. Therefore, extensive further research and development is needed to prove the usability for SHMS purposes and to become sufficiently mature to be used on aircraft.

6.2.8 Corrosion sensor

This technique is based on the principle that the surrounding structure corrodes at the same rate as the sensor. The Corrosion sensor has been used on the Hawk flight test without any result due to not occurring of corrosion

damage. Advanced lab trials at BAE Systems, however, showed the corrosion detection capability of this sensor. On other military aircraft outside AHMOS, trials are performed with prototype systems. Based on the results of these trials BAE claims TRL 7 for this sensor. This could not be acknowledged because this information has not been provided to the AHMOS II community. Therefore, extensive further research and development is needed to become sufficiently mature to be used on aircraft. One of the issues to tackle is in-service data validation.

6.2.9 Fiber optic sensor using reflectometric approach

This work involved testing COTS components and telecommunications as fibres and optical devices to verify the "reflectometer" concept for the detection of the presence of a liquid. A "reflectometer" is a fibre optic sensor based on measuring the reflective index difference between a cut glass fibre and the surrounding environment. The reflection coefficient inside the glass dramatically decreases when the open fibre end is contaminated by liquid.
This is a preliminary study based on defining low cost and robust components, and the range of potential measurements likely. The work also includes some practical investigations on the influence of the fibre optic cut quality on the performance of an eventual sensor. Plastic deformation in the core zone may induce case-by-case variability in the reflected light intensity, leading to a lack of absolute measures for the sensor output.

This basic research has shown the potential of 'reflectometric approach' for SHMS purposes.
The claimed TRL 6 could not be acknowledged. TRL 4 is more appropriate. Therefore, extensive further research and development is needed to prove the usability for SHMS purposes and to become sufficiently mature to be used on aircraft.

6.3 System network and modules

All parts and modules of the system network that have been used and tested during the AHMOS II are whether experimental or prototype parts. During the ground and flight testing it has been proven that they fulfill the functional and performance requirements as needed for the AHMOS II project but that they are not yet fit for definitive in service installation into aircraft. In order to achieve this, these parts should be further developed (including miniaturization) and further tested on ground and in flight for qualification.

Further development areas:

- Data reduction capability (on CC store only data that is relevant)
- Standarisation of interfaces (both hardware and software)

6.4 Data presentation

In this project a Graphical User Interface (GUI) by means of a Notebook System has been developed by DEMEX (NIRAS) in order to present damage data and more to the maintenance personnel. The GUI has been used during the ground tests, the flight tests of the F-18 and the Hawk aircraft.

In three levels information is given about the health status of system and structure to the user: level 1 gives an indication about the status of the system (by means of lights), level 2 gives an indication about the health status of the structure (whether or not damage has been detected) and level 3 gives a graphical presentation of the damage (type, location and dimension). In level 3, also the detailed results of each individual sensing technique, graphs, images etc. can be obtained.
During ground testing at Risø and flight-testing with the Hawk and F-18 aircraft it has been proven that the level 1 and level 2 functionality of the GUI works as expected. Level 3 information as far as available has not completely been used.

Following developments are required before the GUI is suitable for in service use:

- Further improvement of the Level 3 functionality by providing 3D pictures of the monitored structure on which the detected damages are shown. In first instance, for one known structural part with damages the 3D presentation should be further developed, tested and validated.
- Prove 100% reliability of the GUI software.
- Improve the Robustness of the Notebook.
- Enhance download speed of data from the Central Computer.
- Data reduction by storing only relevant data.

6.5 Qualification

For qualification of the SHM Systems both the software and the hardware of the Systems should be qualification tested.

6.5.1 Software qualification

The verification objectives for DO-178B are set in place to detect and report errors that may have been introduced during development processes. Software verification objectives are satisfied through a combination of reviews and analyses, the development of test cases and procedures, and the execution of those test procedures. Reviews and analyses provide an assessment of the accuracy, completeness, and verifiability of the software requirements, software architecture, and source code.
As part of the software qualification process, the system safety assessment is used to determine and categorize the failure conditions and the criticality of a system.

In AHMOS II, Software Critically Level E (Software that could cause or contribute to the failure of the system resulting in no effect on the system) has been selected, because the SHM Systems are introduced for testing purposes only and the failure of the system will not influence the operation of the aircraft.

However, at least the Software Criticality Level C (Software that could cause or contribute to the failure of the system resulting in a major failure condition) should be considered at the commercial introduction of a SHMS in (military) aircraft. This means that Statement Coverage applies for the Structural Coverage Analyses Objective. Statement Coverage means that every statement in the program has been invoked at least once.

6.5.2 Hardware qualification

During AHMOS II extensive amount of hardware qualification testing has been performed.
All the system parts that have been installed in the Hawk pod have successfully been tested on the ground and in flight either by suppliers or by BAE Systems.
All the system parts that have been installed in the F-18 pod have also been ground and flight-tested. Except for an EMI problem (interference on the cockpit audio system) on 3 out of 4 aircraft used, the system passed all tests. The EMI problem could not be resolved in the timeframe of this project because of the slow progress of the flight-testing.
All test results are documented in AHMOS II WE reports.

Further development areas:

- Qualification testing of the actual system to be installed.

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8 ABBREVIATIONS AND ACRONYMS

AE	Acoustic Emission
CAN	Controller Area Network
CC	Central Computer
COTS	Commercial Off The Shelf
EC	Eddy Current
EMC	Electro Magnetic Compatibility
EMI	Electro Magnetic Interference
FBG	Fibre Bragg Grating
FBGS	Fibre Bragg Grating System
FO	Fibre Optic
FOBG	Fibre Optic Bragg Grating
FTP	File Transfer Protocol
GUI	Graphical User Interface
HRI	High Refractive Index
LPG	Long Period Grating
LW	Lamb Wave
NDT	Non Destructive Testing
NS	Notebook System
OEM	Original Equipment Manufacturer
PCB	Printed Circuit Board
POD	Probability Of Detection
SGI	Strain Gauge Indicator
SGSS	Strain Gauge Sensor System
SHM	Structural Health Monitoring
SHMS	Structural Health Monitoring System
SS	Sensor System
SWISS	Smart Wide area Imaging Sensor System
TRL	Technology Readiness Level
VOC	Volatile Organic Compound

9 APPENDICES

APPENDIX 1
Wing Full Scale test (WE1210).
Report is not yet available.

APPENDIX 2
Flight test trials CASA (WE1.3).
Reported in ERG103.015-DOC-1340-0002-EADSCASA-Technical Report-Issue1:

EADS-CASA participates on the European project ERG103.015 “Prototype Demonstration of Structural Health Monitoring System for Military Platforms (AHMOS II)” performing activities related to the following WEs, WE 1.2 “Fatigue Test FBGS” and WE 1.3 “Flight Test Trial”. Also supports Airbus on some activities related to WE 1.1 “Improvement of Sensors and Network Technologies”.
EADS-CASA participates in ERG103.015 developing the FBGS technology based in Bragg´s law. WE 1.2 work was devoted to monitor a ground component with a FBGS system. WE 1.3 work goes further being its scope to verify the ability of the FBGS system to measure in flight conditions.

Results obtained during the flight test campaign performed by EADS-CASA with a C-101 aircraft showed that it is possible to use optical fiber with integrated FBGS, as strain/stress sensors, to develop a Structural Health Monitoring System for Military Platforms.

A good correlation between the stress spectra, generated for the FBGS data recorded, and the vertical acceleration spectrum, obtained with the inertial data device, has been obtained.

The results given by the recording system design, the flight test campaign and the subsequent analysis is considered as a success.

APPENDIX 3
Flight test trials Alenia (WE1.4).
Report is not yet available.